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Spin Forming of an Aluminum 2219-T6 Aft Bulkhead for the Orion Multi-Purpose Crew Vehicle

Phase II Supplemental Report

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December 2015

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October 28, 2015

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Supplemental Report

1.0 Notification and Authorization

The principal focus of this project was to assist the Orion Multi-Purpose Crew Vehicle (MPCV) Program in developing a spin forming fabrication process for manufacture of the aft bulkhead of the pressure vessel. The spin forming process will enable a single piece aluminum (Al) 2219 aft bulkhead which will eliminate the current multiple piece welded construction, simplify fabrication, and lead to an enhanced design that will reduce vehicle weight by eliminating welds. Phase I (NESC-RP-12-00776/NASA TM-2014-218163, (1)) of this assessment explored spin forming the single-piece forward pressure vessel bulkhead from aluminum-lithium (Al-Li) 2195.

The Orion MPCV Program and prime contractor Lockheed Martin (LM) recently made two decisions relative to the NASA Engineering and Safety Center (NESC) Phase I work scope: (1) LM selected the spin forming process to manufacture a single-piece aft bulkhead for the Orion MPCV, and (2) the aft bulkhead will be manufactured from Al 2219 (2).

Based on the Orion MPCV Program's emphasis related to the spin forming process, the NESC was asked to conduct a Phase II assessment to assist in the manufacture of the aft bulkhead and to conduct a feasibility study into spin forming the cone section of the Orion MPCV. The Phase II assessment (NESC-RP-13-00884/NASA TP-2015-218674), (3)) produced and characterized a full scale Al 2219-T62 spin formed aft bulkhead as a pathfinder for the manufacture of the Orion MPCV aft bulkhead. During characterization of the aft bulkhead questions arose regarding stress corrosion cracking (SCC) results and the lack of comparable data in the literature; uniformity of the microstructure; and the impact on properties of the modified heat treatment practice used during production. Based on these questions, a supplementary study was initiated and approved by the NESC. This supplemental report, which is an addendum to the Phase II Spin Formed Aft Bulkhead final report (3), focuses on the results of supplemental mechanical property tests, which attempted to resolve some of these questions.

The Phase II assessment plan was approved on July 18, 2013. Dr. Robert Piascik, NASA Technical Fellow for Materials at the Langley Research Center (LaRC), was selected to lead this assessment. The supplemental testing activity was proposed to and approved by the NESC Review Board on November 20, 2014, during the report out on the Phase II assessment.

The primary stakeholders for this assessment were the NASA Orion MPCV Program and prime contractor Lockheed Martin. Additional benefactors are commercial launch providers developing crew module concepts and all users of Al 2219-T6 spin formed products.

2.0 Executive Summary

The objective of the Phase II Spin Formed Aft Bulkhead study (3) was to assist the Orion Multi-Purpose Crew Vehicle (MPCV) Program in developing a spin forming fabrication process for the manufacture of the aft bulkhead of the pressure vessel. The spin forming process will enable a single piece aluminum (Al) 2219 aft bulkhead resulting in the elimination of the current multiple piece welded construction, simplified fabrication, and an enhanced design that will reduce vehicle weight by eliminating welds. The Phase II assessment produced and characterized a full scale Al 2219-T62 spin formed aft bulkhead as a pathfinder for the manufacture of the Orion MPCV aft bulkhead. During characterization of the pathfinder aft bulkhead some questions arose regarding stress corrosion cracking (SCC) results, uniformity of the microstructure, and the impact on properties of the modified heat treatment practice used by the spin forming vendor, Spincraft. It was also noted that limited data was available in handbooks and open literature for Al 2219-T6 material. This supplemental report[1], which is an addendum to the Phase II Spin Formed Aft Bulkhead final report (3), focuses on the results of supplemental mechanical property tests, which attempted to resolve some of these questions.

Material from the pathfinder aft bulkhead was provided for additional SCC and tensile testing. In addition, plate remnants from the spin forming blank were heat treated using standard and modified practices, and material was provided for SCC, tensile, and fracture toughness testing. The difference in the heat treatment practices is the post-solutionizing quench media; water is used in the standard practice and a water/glycol mixture in the modified practice. The water/glycol mixture results in a slower quench rate, which helps control residual stress and distortion in large parts, but which may alter material properties. Also, material from an Al 2219-T62 spin formed dome produced by Spincraft for NASA's Cryogenic Propellant Storage and Transfer Program (CPST) Program (4), (5) was provided for SCC and fracture toughness testing to represent a comparable product.

The Phase II study SCC test results indicated lower stress corrosion resistance than has been previously documented for Al 2219-T6 material, raising a question about whether the spin forming process compromises SCC resistance. During SCC testing of the aft bulkhead material the only failures that occurred were for specimens tested in the short transverse (ST) orientation, and in particular, one specimen failed at a low enough exposure stress level that, if substantiated, would indicate a need to limit the service stress levels for the aft bulkhead. This result prompted a review of the SCC test standard used for the aft bulkhead, MSFC-STD-3029 (6), compared with American Society for Testing and Materials (ASTM) test methods and practices for SCC evaluation (7) (8) (9), a review of the test procedures, and a review of available literature. Supplemental testing was devised to retest the material to determine whether the one low test result was repeatable and representative of the material, and to examine SCC resistance at additional locations within the aft bulkhead.

No specimen failures occurred during the supplemental SCC tests of the aft bulkhead and post-exposure residual strength levels were above minimum required values. However, post-exposure

[1] Published as NASA-TM-2015-218797

metallurgical analysis revealed SCC in several specimens. All specimens exhibited pitting corrosion and most exhibited intergranular attack. This finding prompted a review of all specimens from the Phase II testing, some of which failed during exposure, to more definitively identify corrosion morphology and the occurrence of SCC. SCC was confirmed in all specimens that failed during the Phase II testing. SCC was not observed in any specimens that survived exposure.

A review of test procedures did not provide an explanation for the difference in results between the Phase II and supplemental SCC tests. Numerous factors can affect the outcome of SCC tests, such as solution chemistry, relative humidity, and applied stress level. The only documented experimental difference was in the condition of the stressing frames. For the Phase II tests the frames were anodized for protection of the frames and to prevent galvanic corrosion. In the supplemental tests a traditional polymer based coating was applied to the frames. It is uncertain whether this created sufficiently different environmental conditions to explain the varied test results. The difference may also be a reflection of inherent material variability.

No failures occurred during supplemental testing of the standard or modified plates. However, the standard plate exhibited higher post-exposure residual strength ratios. Post-exposure metallurgical evaluation showed evidence of SCC only in the modified plate, suggesting that the slower quench rate associated with modified heat treatment reduces stress corrosion resistance. No specimen failures occurred during supplemental tests of the CPST dome material; however, residual strength levels were lower than for the aft bulkhead.

The grain size in the aft bulkhead varied with distance from the pole and through the thickness of the plate, with larger grain sizes noted in regions of greater deformation, typically biased toward the outer mold line (OML) and toward the rim. The variation in grain size stems from the complex and non-uniform deformation induced during spin forming as the plate is shaped over the mandrel. Phase II tensile property testing sampled only the mid-thickness position, which was the most uniform. Supplemental tensile tests were defined to examine the effect of through-thickness variations in grain size on material strength and evaluate the effect of the post-solutionizing quench rate. Supplemental test results confirmed that neither the grain size variations nor the quench rate adversely impacted tensile properties. Tensile strengths were uniform through the thickness of the aft bulkhead and were comparable to the standard and modified plates.

Supplemental fracture toughness testing was performed to determine whether the quench rate impacted toughness and how the aft bulkhead compared with the CPST dome. Fracture toughness behavior of the standard and modified plates, the CPST dome material, and the aft bulkhead were essentially equivalent, with acceptable toughness levels and demonstrated stable tearing.

The supplemental test results combined with the Phase II tests results for the Al 2219-T62 aft bulkhead build confidence that spin forming has no identified barriers for fabrication of the Orion aft bulkhead. Tensile and fracture toughness values were uniform with orientation and location within the aft bulkhead and were comparable to Al 2219-T6 wrought products. SCC

resistance was lower than previously documented for Al 2219-T6 wrought products, likely related to the slower quench rate associated with modified heat treatment. Evidence of SCC was observed in material from the aft bulkhead, CPST dome, and modified plate, based on failure during exposure, residual strength reduction, or occurrence of SCC. These materials all received the modified heat treatment, indicating that the reduced SCC resistance was likely due to the modified heat treatment and not the spin forming process. SCC failures occurred in all three products for material exposed at the minimum exposure stress level used in this study, 50% of the MMPDS ST YS for plate, indicating that the threshold stress level for SCC may be lower.

Recommendations from this study to the Orion MPCV Program include performing SCC testing to identify the threshold stress level for SCC to establish maximum allowable service stress levels. Testing is recommended on multiple spin formed Al 2219-T6 aft bulkhead articles produced during initial serial production and should sample multiple material lots. The SCC test results from this study are for one spin formed aft bulkhead, consequently they represent one material lot and one fabricated production article. In addition, evidence of SCC was observed for all non-zero exposure stress levels indicating that the SCC threshold is below the minimum stress level used in this study. Future testing should include stress levels lower than those used in this study in order to identify a threshold stress level for SCC for Al 2219-T6 spin formed material. It is also recommended that heat treatment studies be performed to determine whether a faster quench rate can be achieved that improves SCC resistance without compromising residual stress and distortion control. SCC results from this study and any additional programmatic testing may be used to develop a Materials Usage Agreement (MUA).

3.0 Background

3.1 Orion MPCV Aft Bulkhead

The primary structural elements of the Orion MPCV pressure vessel, shown in Figure 1, consist of a single piece forged barrel, a multi-piece cone section, a single piece forward bulkhead, a single piece forward tunnel, integrated forward gussets, and a multi-piece welded aft bulkhead. The aft bulkhead configuration shown is assembled from Al-Li 2195 using one circular and two latitudinal welds. The Orion MPCV Program and LM changed to a single-piece aft bulkhead design using spin form fabrication and Al 2219 (2). The motivation for the change in fabrication method was to reduce structural weight by eliminating welds and associated weld lands. The change in material was driven by the single-piece aft bulkhead design, which requires a preform thicker than 2 inches (the current thickness limit for Al-Li 2195) to accommodate all design features. Figure 1 shows the MPCV design at the start of this study and that was used for Exploration Flight Test 1 (EFT-1). In addition to the design changes for the aft bulkhead, the cone section was redesigned to reduce the assembly from twelve to three pieces. These design changes were implemented for Exploration Mission (EM-1) flight article (2).

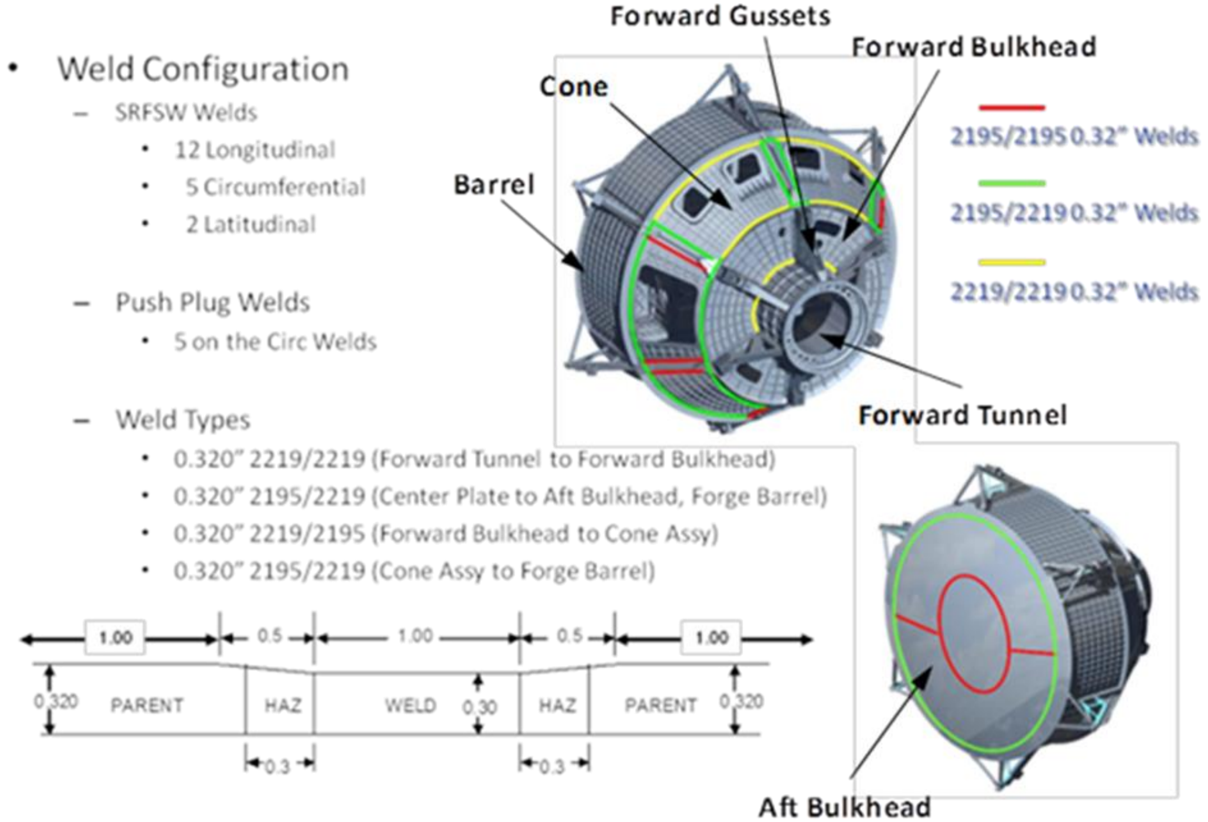


Figure 1. Orion MPCV configuration (Note: dimensions in inches).

3.2 Spin Formed Aft-Bulkhead Pathfinder

The objective of the Phase II project was to spin form an aft bulkhead test article to assess the mechanical properties (e.g., tensile, fracture toughness, and SCC). The study used spin forming to produce a pathfinder article from a single plate (1.5- to 2.5-inch thick) with a curvature similar to the Orion aft bulkhead curvature. For a 100-inch diameter (1.5-inch thick) spin forming blank, preliminary calculations show that a 207.5-inch curvature radius adequately simulated (scaled to) the larger Orion design. Upon completion of spin forming and heat treatment, the pathfinder was sectioned to supply spin formed material to support metallurgical analysis and mechanical property testing, which included a grain size evaluation, tensile and fracture toughness testing, and SCC characterization. Selected pathfinder regions (acreage and thickness locations) were tested to assess uniformity. Analysis of the Phase II test results raised questions about whether the spin forming process adversely impacts SCC resistance, whether post-spin forming heat treatment is detrimental to strength and fracture toughness, and whether observed grain size variations affect properties. Supplemental SCC, tensile, and fracture toughness tests were defined to address some of these questions.

4.0 Supplemental Mechanical Test Program

4.1 Objectives

During the execution of the Phase II mechanical property testing and analysis of the aft bulkhead, several issues arose, which the NESC team attempted to address to assist the LM MPCV design team in their first article test program. In addition, several findings were observed that the team wished to further analyze to clarify the results. The team proposed a limited number of supplemental SCC, tensile, and fracture toughness tests, which were accepted by the NESC advisory team. Further details on these supplemental tests are addressed in Sections 5 through 7. Due to project milestones and schedule, the results from these supplemental tests were not included in the Phase II Spin Formed Aft Bulkhead final report (3), but are presented here as an addendum.

5.0 Supplemental Stress Corrosion Tests

5.1 Background

During SCC testing of the aft bulkhead material the only failures that occurred were for specimens tested in the ST orientation. Specimen failures occurred in three of the four coupon blank locations tested at exposure stress levels of 75% of the material yield strength (YS). One specimen from the M10 coupon blank failed at an exposure stress of 50% of the material YS. These results raised questions about the SCC resistance of the aft bulkhead material in comparison with other wrought products. The failure at 50% YS exposure stress raised concern because of the impact on SCC resistance table ratings and threshold stress level, which is used, in part, to identify the maximum allowable service stress. A key question guiding the supplemental testing was whether this failure was repeatable.

Additional questions arose when making comparisons with handbook and published data in an attempt to interpret the SCC results. A complication that impeded interpreting the results was that there is limited SCC data available for Al 2219-T6 products. In addition, several questions arose regarding the available data for Al 2219-T8 products, both in terms of SCC test practices and the available data to substantiate published ratings. In particular, what should be the appropriate basis for the applied stress level? There are a number of applicable standards for SCC testing that use different applied stress levels, exposure periods, and criterion ratings (7), (8), (9), (10). Most standards establish exposure stress levels based on the Metallic Materials Properties Development and Standardization (MMPDS) Handbook (11) allowable YS, but the Marshall Space Flight Center (MSFC) SCC test standard, MSFC-STD-3029 (6), which was used for the aft bulkhead testing, uses exposure stress levels based on the measured YS for the product being tested. The MMPDS design allowable material properties are generally lower due to the statistical analysis, consequently using the actual material properties results in higher exposure stress levels and a more severe test than the handbook data being used for comparison. Also, the measured YS of the aft bulkhead was higher in the ST orientation than the longitudinal (L) and long transverse (LT) orientations so the ST specimens experienced the highest exposure stress

levels. No design values exist for spin formed products so testing according to standards that base exposure stress levels on MMPDS requires using values for plate. MMPDS provides design allowables for plate in the L and LT orientations only so these values are used in testing where exposure stress levels are based on MMPDS and for all orientations. Specimens exposed at stress levels of 50 and 75% of measured ST YS for the aft bulkhead were equivalent to exposures at 60 and 90% of the MMPDS YS values for plate, illustrating the more aggressive test conditions experienced in the current study as compared to the literature reference data.

To address the issue of exposure stress level, additional SCC tests were conducted on coupon blank M10 using applied stress levels based on MMPDS A-basis design allowables for Al 2219-T62 plate. To further verify and interpret the SCC results, additional tests were also conducted on coupon blanks at other locations within the aft bulkhead, other spin formed products, and wrought plate materials. Table 1 lists the SCC test matrix and the questions being addressed. These supplemental SCC tests consisted of 30-day alternate immersion in a 3.5% sodium chloride (NaCl) environment and only evaluated the ST orientation since this is the grain orientation most susceptible to SCC and the orientation of the failures in question. The goal of the supplemental SCC test matrix was to ensure confidence in the Phase II data that had been generated, and characterize the aft bulkhead component as best as possible.

Additional general questions arose regarding how the SCC ratings in published literature were established. What type of SCC data will the Orion MPCV Program use to base their design? What is the threshold stress level for SCC for the aft bulkhead? Due to limited funds and schedule, not all of these questions can be addressed in the scope of this supplemental SCC test program.

Table 1. Supplemental SCC test matrix and questions being addressed.

Material Source	Location / Heat Treatment	Applied Stress Level, % YS	Applied Stress Level, ksi	Orient.	# of Specimens	Question Addressed
Aft Bulkhead	M10	50 based on M10 avg. ST YS	22.2	ST	3	1. Is failure at 50% exposure stress repeatable? Was this data point an outlier or it is representative of this aft bulkhead location?
		75 based on M10 avg. ST YS	33.3	ST	3	
		50 based on MMPDS LT YS	18	ST	3	2. Does material pass at exposure stress levels based on MMPDS design properties rather than actual material yield strength?
		75 based on MMPDS LT YS	27	ST	3	
Aft Bulkhead	J1	0	0	ST	3	3. What is the SCC behavior in other coupon blank locations along a different meridian line?
		50 based on MMPDS LT YS	18	ST	3	
		75 based on MMPDS LT YS	27	ST	3	
Aft Bulkhead	J2	0	0	ST	3	
		50 based on MMPDS LT YS	18	ST	3	
		75 based on MMPDS LT YS	27	ST	3	
Aft Bulkhead	J3	0	0	ST	3	
		50 based on MMPDS LT YS	18	ST	3	
		75 based on MMPDS LT YS	27	ST	3	
Plate	Standard	0	0	ST	3	4. Does spin forming alter the SCC resistance of plate?
		50 based on MMPDS LT YS	18	ST	3	
		75 based on MMPDS LT YS	27	ST	3	
Plate	Modified	0	0	ST	3	5. Does the quench rate affect SCC resistance of plate?
		50 based on MMPDS LT YS	18	ST	3	
		75 based on MMPDS LT YS	27	ST	3	
CPST Spin Formed Dome	Pole	0	0	ST	3	6. How does the aft bulkhead compare with other spin formed domes?
		50 based on MMPDS LT YS	18	ST	3	
		75 based on MMPDS LT YS	27	ST	3	
CPST Spin Formed Dome	Rim	0	0	ST	3	
		50 based on MMPDS LT YS	18	ST	3	
		75 based on MMPDS LT YS	27	ST	3	

Aft bulkhead M10 ST YS = 44.4 ksi
MMPDS LT YS = 36 ksi

The first priority of these supplemental SCC tests was to repeat the tests on coupon blank M10 to determine whether the one specimen failure that occurred at 50% YS applied stress level was repeatable. The concern was that if this result was repeatable it would indicate a threshold stress level for SCC low enough that service stress levels for the aft bulkhead would be lower than acceptable for the current design. These first priority tests repeated the tests for material from coupon blank M10 with the applied stress levels based on measured YS values established from baseline tensile test data for the coupon blank to determine if the results were repeatable. Additional tests from this coupon blank were also conducted at applied stress levels based on MMPDS design values to determine whether or not the material would pass at the resulting lower exposure stress levels.

The second priority tests were in response to requests from the Orion MPCV Program to better understand the SCC resistance throughout the aft bulkhead. The SCC specimens from coupon blanks J1, J2, and J3 designated for seacoast exposure SCC testing were re-directed to alternate immersion SCC testing to examine more locations in the aft bulkhead. Seacoast exposure SCC testing was proposed in the original test program because of concerns that the alternate immersion test results could become obscured because of general corrosion in the form of pitting. Seacoast exposure SCC testing, which is performed in a less aggressive outdoor environment and requires longer test durations than the standard accelerated corrosion tests performed in a laboratory, is used as a complementary test to alternate immersion. Based on the Phase II alternate immersion SCC test results, the NESC team decided that obtaining additional data through the accelerated laboratory test was a higher priority. These seacoast exposure SCC test specimens had been machined and loaded in the stressing frames; the only change required was to change the applied stress levels and install them in the alternate immersion test apparatus. For these tests, the applied stress level was based upon MMPDS A-basis design properties for plate. These specimens offered a ready opportunity to generate the additional data while staying within the prescribed budget and schedule.

The third priority tests were in response to the limited SCC data for Al 2219-T6 products and the unknown effects of material processing on SCC performance. The SCC resistance of the aft bulkhead was lower than that reported for Al 2219-T6 wrought products. These tests attempted to determine if this was inherent to this plate lot or due to the spin forming process. It is not possible to isolate the effects of spin forming processing alone because these components typically receive a post-fabrication heat treatment. However, to evaluate the impact of the modified heat treatment used on the aft bulkhead, tests were performed on remnant F temper plate from the aft bulkhead spin forming blank (i.e., no spin forming deformation) processed to the T62 temper using both standard and modified heat treat procedures as outlined in Section 6.3. The primary difference between the two heat treat processes was the post-solution heat treatment quench media and the associated cooling rates. The standard heat treatment uses a water quench, which results in a faster quench rate than the water/glycol quench mixture used for the modified heat treatment. Remnant spin formed Al 2219-T62 dome material from the CPST program (5) was tested to provide data for a comparable product form. For these tests on processed plate and the CPST dome material, the applied stress levels were based upon MMPDS A-basis design properties for plate since there are no design values for Al 2219-T6 spin formed products. For consistency plate values were used in testing of the CPST dome rather than measured values from the dome.

5.2 Test Procedures

The location of aft bulkhead coupon blanks tested in the Phase II and supplemental tests are shown in the aft bulkhead cut plan (Figure 2) and coupon blank matrix (Table 2). Coupon blanks M7, M8, M9, and M10 were evaluated in the Phase II testing while coupon blanks M10, J1, J2, and J3 were evaluated in the supplemental testing. The J1 – J3 coupon blanks were originally designated for seacoast exposure SCC testing, but were re-directed to the supplemental SCC tests

program. As such these specimens had been machined and loaded in the test frames. For each coupon blank, MSFC received 9 specimens pre-assembled and loaded in the test fixture and 1 extra specimen. Since the loads applied did not correspond to the loads in the supplemental test plan, these specimens were unloaded and reloaded to the appropriate exposure stress. The 9 reloaded specimens from each coupon blank were used for the supplemental SCC testing while the one extra specimen was used for baseline tensile testing. An additional 18 specimens were machined in the ST orientation from coupon blank M10, 9 each for testing at exposure stress levels based on MMPDS and the measured YS.

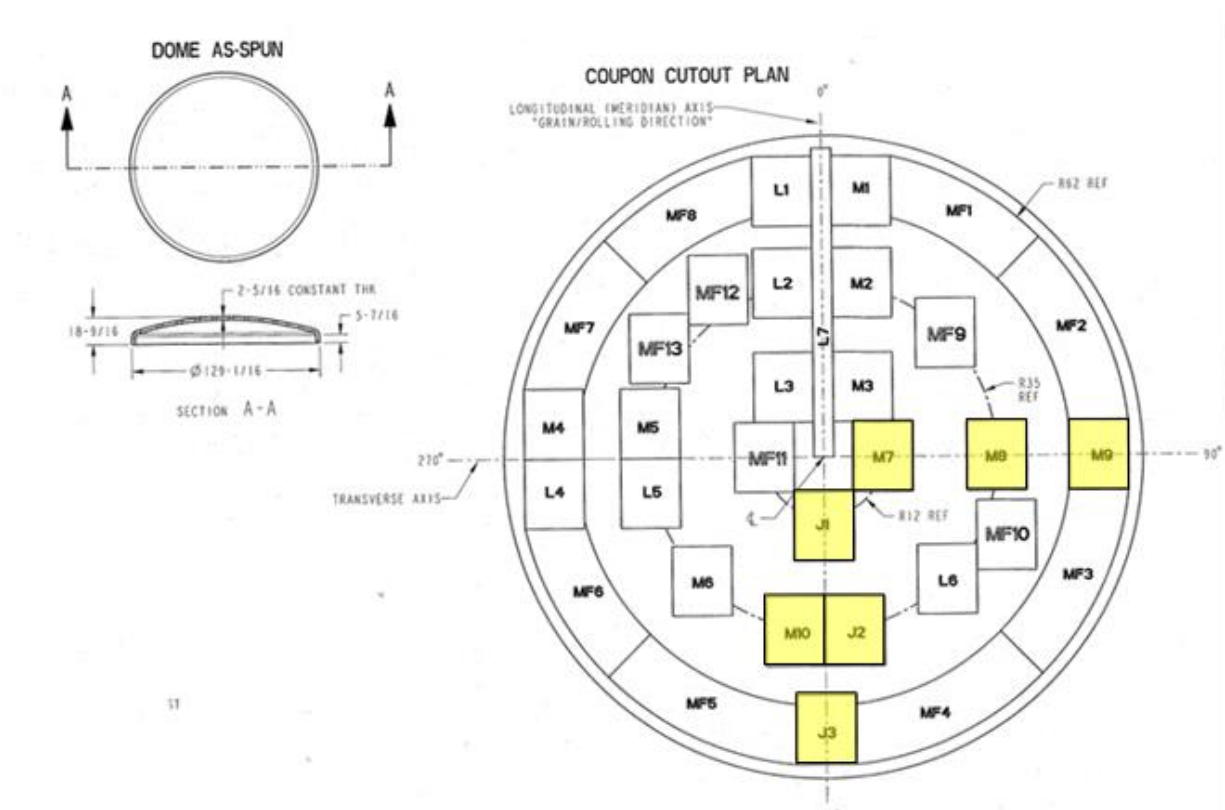


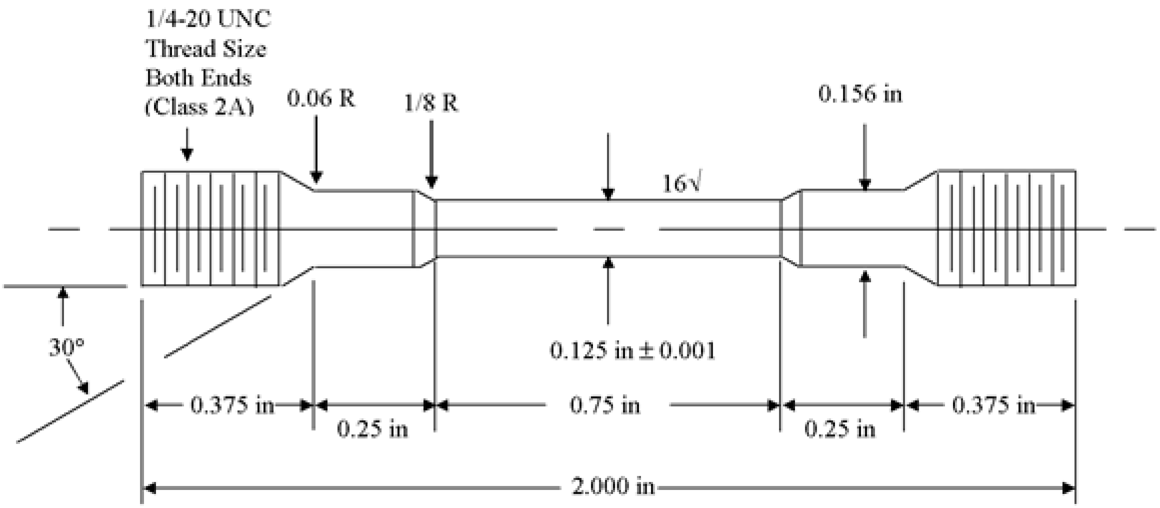
Figure 2. Diagram showing coupon blank locations for SCC tests of the spin formed aft bulkhead.

Table 2. SCC coupon blank locations and orientations.

Coupon Blank	Coupon Blank Size		Coupon Center Point	
	Longitudinal Dimension, in	Transverse Dimension, in	Meridian Angle, degrees	Arc Length from CL, in.
M7	14	12	90	12
M8	14	12	90	35-1/8
M9	14	12	90	56-1/4
M10	14	12	190	35-5/8
J1	14	12	180	12
J2	14	12	170	35-5/8
J3	14	12	180	55-5/8

Additional test material consisted of remnant Al 2219-F wrought plate from the aft bulkhead spin forming blank heat treated to the T62 temper using two heat treat variants as described in Section 6.3 and remnant material from the pole and rim regions of a spin formed Al 2219-T62 CPST dome. For the plate and CPST dome material, 12 ST tension specimens were machined, oriented with respect to the original plate rolling direction. Three specimens from each set of 12 were used to obtain baseline tensile data to assist in characterizing the effects of stress and exposure on SCC; the remaining 9 were used for SCC testing.

All specimens for the supplemental SCC tests were machined in the ST orientation per the ASTM E8 (12) small-size round tension test specimen design shown in Figure 3. Baseline tensile tests were conducted for each lot of material using the same specimen design to assist in characterizing the effects of stress and exposure on SCC.



NOTES:
1. Tolerances: ± 0.005 inch, except otherwise specified.
2. Surface finish: 16√ for the reduced section, 32√ for the rest.
3. Thread dimensions must be as specified. Measurement by fabricator is mandatory.
4. No undercutting of radii permitted.
5. Gage section to be concentric with axis within 0.002 inch TIR and parallel.
6. No file marks or nicks permitted within gage section.
7. Center-drilling permissible (both ends). May use a #1 size max. Chamfer diameter not to exceed 0.100 in.
8. Break sharp edges.
9. The reduced section may have a gradual taper from the ends toward the center with the ends not more than 0.005 inch larger diameter than the center.

Figure 3. Round sub-size tensile specimen design used for SCC testing (12).

The SCC testing and analysis were performed in accordance with MSFC-STD-3029 (6). The SCC specimens were tested using the direct tension loading method as described in ASTM G49 (9). Constant strain stressing frames were used to determine the applied stress levels from measurement of the strain where average linear stress (σ) is proportional to the average linear strain (ε), $\sigma/\varepsilon = E$, where the constant E is the modulus of elasticity. As per the test matrix shown in Table 3; three replicate SCC specimens from each group were loaded in tension to 50 and 75% of the MMPDS A-basis LT YS (36 ksi), which correspond to an applied stress of 18 and 27 ksi, respectively. Additional specimens from coupon blank M10 were stressed to 50 and 75% of the average YS value (44.41 ksi) obtained from baseline tensile tests of the coupon blank M10, which correspond to an applied stress of 22.2 and 33.3 ksi, respectively. These stress levels correspond to 62% and 93% of the MMPDS A-basis YS, which illustrates the discrepancy between test methods and potential difficulties in comparing results. In the case of the aft bulkhead, an exposure stress of 75% of the measured YS equates to more than 90% of the MMPDS value. More importantly, the 50% exposure stress based on measured YS is 62% of the

MMPDS value. Control specimens with no applied stress were also tested in all groups for comparison.

All specimens were subjected to alternate immersion exposure in a 3.5% NaCl solution for a test duration of 30 days per ASTM G44 (7). Three replicate specimens were tested for each stress level and test group as per the SCC test matrices shown in Table 3.

Table 3. Supplemental SCC test matrix.

Material Source	Location / Heat Treat	Orient.	UTS[(1)] ksi	YS[(1)] ksi	MMPDS LT YS[(2)] Stress Level % YS	MMPDS LT YS[(2)] Stress Level ksi	Actual ST YS Stress Level % YS	Actual ST YS Stress Level ksi
Aft Bulkhead	M10 Membrane	ST	59.65	44.41	0	0	0	0
					50	18	50	22.2
					75	27	75	33.3
Aft Bulkhead	J1 Pole	ST	55.09	41.88	0	0	-----	-----
					50	18	-----	-----
					75	27	-----	-----
Aft Bulkhead	J2 Membrane	ST	57.04	43.11	0	0	-----	-----
					50	18	-----	-----
					75	27	-----	-----
Aft Bulkhead	J3 Rim	ST	58.05	43.81	0	0	-----	-----
					50	18	-----	-----
					75	27	-----	-----
Plate	Standard	ST	62.07	43.50	0	0	-----	-----
					50	18	-----	-----
					75	27	-----	-----
Plate	Modified	ST	59.15	37.19	0	0	-----	-----
					50	18	-----	-----
					75	27	-----	-----
CPST Dome	Pole	ST	56.30	40.18	0	0	-----	-----
					50	18	-----	-----
					75	27	-----	-----
CPST Dome	Rim	ST	57.56	37.33	0	0	-----	-----
					50	18	-----	-----
					75	27	-----	-----

(1) Average UTS and YS obtained from baseline tensile tests of unexposed specimens
(2) MMPDS A-basis LT YS = 36 ksi

Specimens were considered to have failed by SCC if the specimens fractured during exposure, the residual tensile strength was below the specified threshold, or the specimens exhibited cracking during post-exposure visual and metallographic examination.

If no specimens fractured during exposure for a given test condition, then one specimen from the set was subjected to metallographic examination while the remaining two specimens were loaded to failure in tension to determine residual tensile strength. Two measures were used to evaluate

the residual tensile strength of the surviving specimens: the percent tensile strength retained, which compares the residual tensile strength of the exposed specimens to the average tensile strength of unexposed specimens; and the residual strength ratio, which compares the residual tensile strength of specimens exposed with and without an applied stress. These criteria enable quantification of the effects of general corrosion thus reducing the experimental interferences associated with the more subjective visual examination of specimens (13).

The percent tensile strength retained provides a measure of the residual load carrying ability of the exposed specimens compared to unexposed specimens, and is an indication of the reduction in specimen cross-sectional area, not a change in strength of the material. Loss in cross-sectional area can be due to general corrosion, pitting, and/or stress corrosion. Metallurgical examination is required to confirm the type of corrosion. For the specimens tested with an applied stress, the reduction in tensile strength is due to the combined effect of stress and the corrosive environment. For the specimens tested with no applied stress the reduction in tensile strength is due to the effect of the corrosive environment only. The percent tensile strength retained for each exposed specimen was calculated as:

$$\text{Percent Tensile Strength Retained} = (UTS_f/UTS_i) \times 100$$

where:

UTS_f = Residual strength of the exposed specimen (failure load / original specimen cross-sectional area)
UTS_i = Average ultimate tensile strength for the unexposed specimens.

The residual strength ratio for each specimen that was exposed with an applied stress was calculated as:

$$\text{Residual Strength Ratio} = UTS_s/UTS_o$$

where:

UTS_s = Residual strength of stressed and exposed specimen
UTS_o = Averaged residual strength of non-stressed and exposed specimens

The residual strength ratio provides a more direct indication of the effect of applied stress during exposure and therefore a method to separate the effects of general corrosion and pitting from stress corrosion. The UTS_s and UTS_o are calculated based on original specimen cross-sectional area, and provide an indication of the loss in area due to stress corrosion and general corrosion, respectively. For this study, specimens with residual strength ratios of less than 0.75 were considered failures. This threshold for the residual strength ratio was based on heritage SCC test data generated at MSFC.

Specimens that fractured were sectioned and examined metallographically to verify that SCC was the cause of the fracture. If no failures occurred for a set of replicate specimens then one was examined to determine whether SCC occurred. Guidelines that were used to identify SCC in Al alloys include (1) cracks that follow an intergranular path or mixed intergranular - transgranular path were considered as SCC; (2) exclusively transgranular cracks that initiated at corrosion pits were not considered as SCC; and (3) intergranular cracks that were no deeper than the width of localized areas of intergranular corrosion were not considered as SCC (14). In this study additional criteria that guided classification of an observed crack to be due to stress corrosion were that the crack length extended beyond the depth of pitting or intergranular attack, the crack branched, and / or that the crack initiated on the specimen surface.

One goal of MSFC-STD-3029 is to establish ratings for SCC resistance. The table rating requirements are shown below for reference. It should be noted that while table ratings are important, for design purposes a threshold stress level for SCC must be identified to establish maximum allowable service stress levels. Also, the collective data from the Phase II and supplemental SCC tests are not sufficient to define a threshold value or establish table ratings. Both the Phase II and supplemental testing was performed on the same Al 2219-T6 spin formed aft bulkhead; consequently, this represents one material lot and one single fabrication article. There are no standards or test guides that define the number of tests required to establish a threshold stress level for SCC and the requirements will be unique for a specific combination of product form, material, and anticipated service conditions.

Table I Requirements
Alloys, tempers, and weldments in Table I are considered highly resistant to SCC in 3.5% NaCl alternate immersion or 5% salt spray. An alloy or weldment can be added to this table if no stress corrosion failures occur on specimens stressed to 75% of the YS within 30 days of exposure.

Table II Requirements
Alloys, tempers, and weldments in Table II are considered moderately resistant to SCC in 3.5% NaCl alternate immersion or 5% salt spray. An alloy or weldment is added to this table if no stress corrosion failures occur on specimens stressed to 50% of the YS within 30 days of exposure.

Table III Requirements
Alloys, tempers, and weldments in Table III are considered to have low resistance to SCC in 3.5% NaCl alternate immersion or 5% salt spray. They are placed in this table if stress corrosion failures occur on specimens stressed to 50% of the YS within 30 days of exposure.

5.3 Stress Corrosion Results

The supplemental SCC tests results for the 30-day alternate immersion exposure are presented in Table 4. No SCC failures occurred in the ST specimens during the 30-day alternate immersion exposure for specimens from the aft bulkhead, standard or modified plates, or the CPST dome. Results from the Phase II SCC tests of the aft bulkhead are provided in Table 5 for comparison and illustrate that specimen failures occurred in three of the four coupon blank locations at 75% YS exposure stress, and in coupon blank M10 at 50% YS exposure stress.

For the supplemental tests, one of the three replicate specimens from each test group was metallographically examined. The remaining two replicate specimens from each test group were tensile tested to determine residual tensile strength remaining after exposure with the results used to determine residual tensile strength retained and the residual strength ratio. The individual and average tensile strengths of the supplemental materials obtained from baseline tensile tests are shown in Table 6 and were used to determine residual tensile strength for the surviving SCC specimens.

Residual tensile strength results for the supplemental tests are shown in Table 7 for specimens exposed with an applied stress and in Table 8 for specimens exposed without applied stress. For the specimens from the aft bulkhead which were exposed with an applied stress the percent tensile strength retained ranged from 51 to 73% compared to a range of 40 to 69% for specimens exposed without an applied stress. The highest percentages were for the specimens from coupon blank J3, obtained from the rim area of the bulkhead while the lowest were for specimens from coupon blank J1 near the pole. A graphical representation of the overall reduction in residual strength for the exposed specimens is presented in Figure 4. The baseline stress-strain curves for specimens from all material lots prior to exposure are shown in Figure 4(a) while Figure 4(b) shows the stress-strain curves for the exposed specimens. The curves are not identified and are presented to show the reduction in residual strength resulting from the exposure. In comparison, as shown in Table 9, for the Phase II tests the percent tensile strength retained for the specimens exposed with an applied stress ranged from 4 to 55% compared to the specimens tested without an applied stress, which ranged from 32 to 49%. The lowest values were for the 50% YS exposure stress specimens from coupon blank M10 (membrane) and the highest from coupon blank M9 (rim). For the CPST dome material percent tensile strength retained values ranged from 34 to 59 with the highest values from the rim. Based on the percent tensile strength retained from the Phase II and supplemental testing of the aft bulkhead combined with the limited testing of the CPST dome, there is some variability in SCC resistance throughout the aft bulkhead, and potentially in similar spin formed components, with regions near the rim having greater resistance.

The percent tensile strength retained for specimens obtained from the standard and modified plates were similar, indicating that there was no significant effect of the heat treatments on SCC resistance. Percent tensile strength retained values ranged from 52 to 63 for the modified heat treat and from 45 to 57 for the standard heat treat.

The residual strength ratios shown in Table 7 and Table 8 were used in this study as an additional failure criteria, with a value of 0.75 defined as the threshold for passing. All of the specimens from the supplemental tests of the aft bulkhead passed as did all of the Phase II tests, with the exception of the 50% YS exposure stress level (specimens # 153 and 154) from the Phase II tests of coupon blank M10. All specimens from the standard and modified plates passed this test. Five of the eight specimens from the CPST dome passed. Two of the specimens that failed were obtained from the pole, one with a ratio of 0.58 had been exposed at 50% of LT MMPDS YS (44.8% of measured ST YS) and one with a ratio of 0.73 had been exposed at 75% of LT MMPDS YS (67.2% of measured ST YS). The third specimen that failed the residual strength ratio test with a ratio of 0.73 was from the CPST dome rim area and had been exposed at 75% of the LT MMPDS YS (72.3% of measured ST YS). The average ratios for all materials evaluated in the supplemental tests (from best to worst) were 1.11 for M10, 1.10 for standard plate, 1.04 for J2, 0.99 for J3, 0.97 for J1, 0.89 for modified plate, 0.87 for CPST rim, and 0.74 for CPST pole. While not a rigorous comparison, the residual strength ratios indicate that the aft bulkhead had slightly better SCC resistance that the CPST dome and the standard heat treatment was slightly more resistant than the modified heat treatment.

Metallographic examination was used to evaluate whether SCC was the cause of specimen failures during exposure and to determine whether SCC occurred in specimens that survived exposure. Photomicrographs of one of the three replicate specimens from each supplemental test group are shown in Figure 5 through Figure 12. For each sample set, a low magnification view of the exposed specimen is shown with low and high magnification photomicrographs of the polished cross-section in the etched and unetched conditions. The presence or absence of SCC was noted for each specimen and primary SCC features were encircled. Pitting was apparent on all specimens, however, the effect was not sufficiently detrimental to cause failures within the 30-day exposure period. Additionally, intergranular corrosion was present in many samples, primarily from the aft bulkhead and modified plate. According to electrochemical theory, Al alloys that contain appreciable amounts of soluble alloying elements such as Cu, Mg, Si, and Zn are susceptible to grain boundary corrosion, including both intergranular and stress corrosion (15). Specimen J1-8, Figure 6(a), shows a typical example of intergranular corrosion observed in these samples. SCC was observed in samples from the aft bulkhead, CPST dome, and modified plate as noted in the micrographs (encircled in red); however, the extent was not sufficiently detrimental to cause failure within the 30 day exposure period. SCC was not observed in the standard plate. From aft bulkhead coupon blank M10, specimens M10-6 (Figure 5(b), 50% YS (measured)); M10-15 (Figure 5(c), 50% YS (MMPDS)); M10-9 (Figure 5(d), 75% YS (measured)); and M10-16 (Figure 5(e), 75% YS (MMPDS)) showed SCC. Specimens J1-2 from coupon blank J1 at 75% YS (Figure 6(c)) and specimen J2-5 from coupon blank J2 at 50% YS (Figure 7(b)) showed evidence of SCC. For the case of other product forms, specimen GQ-4 (Figure 10(b)) from the modified plate, and specimens CP-P9 (Figure 11(c)) and CP-R7 (Figure 12(c)) from the CPST dome showed evidence of SCC.

The observation of SCC in the supplemental test specimens that survived exposure prompted a review of all specimens from the Phase II testing at stress levels and exposure periods similar to

those used in the supplemental testing. Photomicrographs of the LT and ST specimens from the Phase II testing are provided in Appendix A (Figure A-1 - Figure A-4; Section 11.1) and Appendix B (Figure B-1 - Figure B-4; Section 11.2), respectively. The LT specimens exhibited pitting and intergranular attack, but SCC was not observed. The ST specimens exhibited pitting and intergranular attack and SCC was confirmed in nearly all samples that failed during exposure. SCC was not observed in any specimens that survived exposure.

A summary compilation of the supplemental tests results for each individual specimen is shown in Appendix C, Table C-1. This table includes the test conditions, pass/fail, residual strength, and metallographic examination results cross-referenced with the location in the report of the relevant photomicrograph figure number. A similar summary compilation for the Phase II test results is shown in Appendix D, Table D-1, for the LT orientation and Table D-2 for the ST orientation.

Also noted in the supplemental test specimens was that the grain size in samples from the aft bulkhead coupon blanks (Figures 5-8) and the standard and modified plates (Figures 9 and 10) were similar to one another, but smaller than in samples from the CPST dome material (Figures 11 and 12). The difference in grain size was not quantified, but may have contributed to a greater extent of pitting and the lower residual strength ratios in the CPST dome material.

A review of test procedures did not provide an explanation for the difference in the occurrence of failures during exposure for the Phase II and supplemental SCC tests. Numerous factors can affect the outcome of SCC tests, such as solution chemistry, relative humidity, and applied stress level. The only documented experimental difference was in the condition of the stressing frames, which were fabricated from Al 6061. For the Phase II tests the frames were anodized for protection of the frames and to minimize any galvanic effects on the Al 2219 specimen. Since the anodized coating is considered non-conductive and the two alloys (i.e., Al 2219 and Al 6061) are considered galvanically-compatible, no galvanic effects were anticipated. In the supplemental testing the stressing frames were coated with a plastic compound for extra galvanic protection. The extra isolation of the frames may have more fully suppressed galvanic effects; however, it is uncertain whether this created sufficiently different environmental conditions to explain the varied test results. The failure that occurred in the 50% YS exposure stress level specimen from coupon blank M10 during the Phase II testing was not repeatable.

The pass/fail results, percent tensile strength retained, residual strength ratio, and results of metallurgical examination for all of the materials evaluated in both the Phase II and supplemental test phases of this study indicate that the spin forming process and associated modified heat treat practice reduces the SCC resistance of Al 2219-T6 material when compared with handbook rankings for Al 2219-T6 wrought products. The reduced SCC resistance was likely due to the slower quench rate experienced during the modified heat treatment as compared with the standard heat treatment. Evidence of SCC was observed in material from the aft bulkhead, CPST dome, and modified plate, which all received the modified heat treatment. SCC failures occurred in all three products for material exposed at the minimum used in this study, 50% of the MMPDS ST YS for plate (18 ksi), based on either failure during exposure, residual strength reduction, or occurrence of SCC. It should be noted that the data from this study provides an

indication of SCC resistance, but additional data will be needed to confirm trends noted and to establish a threshold stress level for SCC. It is recommended that additional testing be performed by the Orion MPCV Program or other end users of spin formed Al 2219-T6 products. This study sampled one spin formed aft bulkhead and consequently only one material lot. Additional testing should be performed on multiple articles from initial serial production and should sample multiple material lots. It is also recommended that heat treatment studies be performed to determine whether a faster quench rate can be achieved that improves SCC resistance without compromising residual stress and distortion control.

Table 4. Supplemental SCC test results for spin formed Al 2219-T62 aft bulkhead, CPST dome and wrought plate materials following 30-day 3.5% NaCl alternate immersion exposure.

Material Source	Location / Heat Treat	Orient.	UTS(1) ksi	YS(1) ksi	Applied Stress Level ksi	Applied Stress Level % Actual ST YS	Applied Stress Level % MMPDS LT YS(2)	Failure Ratio(3)	Days to Failure
Aft Bulkhead	M10 Membrane	ST	59.65	44.41	0	0	0	0/3	NF in 30 days
					18	40.5	50	0/3	NF in 30 days
					27	60.8	75	0/3	NF in 30 days
					22.2	50	61.7	0/3	NF in 30 days
					33.3	75	92.5	0/3	NF in 30 days
Aft Bulkhead	J1 Pole	ST	55.09	41.88	0	0	0	0/3	NF in 30 days
					18	43.0	50	0/3	NF in 30 days
					27	64.5	75	0/3	NF in 30 days
Aft Bulkhead	J2 Membrane	ST	57.04	43.11	0	0	0	0/3	NF in 30 days
					18	41.8	50	0/3	NF in 30 days
					27	62.6	75	0/3	NF in 30 days
Aft Bulkhead	J3 Rim	ST	58.05	43.81	0	0.0	0	0/3	NF in 30 days
					18	41.1	50	0/3	NF in 30 days
					27	61.6	75	0/3	NF in 30 days
Plate	Standard	ST	62.07	43.50	0	0	0	0/3	NF in 30 days
					18	41.4	50	0/3	NF in 30 days
					27	62.1	75	0/3	NF in 30 days
Plate	Modified	ST	59.15	37.19	0	0	0	0/3	NF in 30 days
					18	48.4	50	0/3	NF in 30 days
					27	72.6	75	0/3	NF in 30 days
CPST Dome	Pole	ST	56.30	40.18	0	0	0	0/3	NF in 30 days
					18	44.8	50	0/3	NF in 30 days
					27	67.2	75	0/3	NF in 30 days
CPST Dome	Rim	ST	57.56	37.33	0	0	0	0/3	NF in 30 days
					18	48.2	50	0/3	NF in 30 days
					27	72.3	75	0/3	NF in 30 days

(1) Average UTS and YS values obtained from baseline tensile tests of unexposed specimens.
(2) MMPDS A-basis LT YS = 36 ksi.
(3) Failure ratio = number of failures divided by total number of specimens tested.

Table 5. Phase II SCC test results for spin formed Al 2219-T62 aft bulkhead material following 30-day 3.5% NaCl alternate immersion exposure.

Coupon Blank	Meridian Angle	Orient.	UTS ksi	YS ksi	Stress Level % YS	Stress Level ksi	Failure Ratio[3]	Days to Failure
M7	90°	ST	57.87	43.2	0	0	0/3	No failures
					50	21.6	0/3	No failures
					75	32.4	3/3	26, 28, 30
M8	90°	ST	58.69	43.73	0	0	0/3	No failures
					50	21.87	0/3	No failures
					75	32.8	3/3	27, 30, 30
M9	90°	ST	59.86	44.33	0	0	0/3	No failures
					50	22.17	1/3[1]	30[1]
					75	33.25	0/3	No failures
M10	190°	ST	59.65	44.41	0	0	0/3	No failures
					50	22.21	1/3[2]	29
					75	33.31	2/3	26, 30

(1) Invalid failure. Failed in the shoulder outside of the gage length.

(2) The two specimens that did not break apart during exposure did not pass the residual tensile strength ratio test and can also be considered failures.

(3) Failure ratio = number of failures divided by total number of specimens tested.

Table 6. Baseline tensile properties of the Al 2219-T62 supplemental test materials.

Material Source	Location / Heat Treat	Orient.	Specimen No.	UTS ksi	YS ksi	E Msi	e %
Aft Bulkhead	M10 Membrane	ST	M10-19	59.44	44.57	9.98	4.76
			M10-20	59.59	44.79	10.04	5.01
			M10-21	59.92	43.88	10.34	4.73
			Average	**59.65**	**44.41**	**10.12**	**4.83**
Aft Bulkhead	J1 Pole	ST	J1-10	55.09	41.88	9.84	4.58
Aft Bulkhead	J2 Membrane	ST	J2-10	57.04	43.11	10.14	5.13
Aft Bulkhead	J3 Rim	ST	J3-10	58.05	43.81	10.01	5.68
Plate	Standard	ST	WQ-10	62.41	42.44	9.85	5.03
			WQ-11	61.77	44.42	10.82	4.61
			WQ-12	62.02	43.63	11.92	4.21
			Average	**62.07**	**43.5**	**10.86**	**4.62**
Plate	Modified	ST	GQ-10	60.27	35.75	10.18	4.94
			GQ-11	57.95	36.31	9.67	4.75
			GQ-12	59.24	39.52	11.31	4.67
			Average	**59.15**	**37.19**	**10.39**	**4.79**
CPST Dome	Pole	ST	CPP-10	55.4	41.74	10.79	3.06
			CPP-11	57	40.77	10.1	3.86
			CPP-12	56.5	38.02	9.81	4.01
			Average	**56.3**	**40.18**	**10.23**	**3.64**
CPST Dome	Rim	ST	CPR-10	57.42	36.91	9.89	4.31
			CPR-11	57.18	35.97	10.33	4.89
			CPR-12	58.08	39.11	9.89	3.99
			Average	**57.56**	**37.33**	**10.04**	**4.40**

Table 7. Residual load carrying ability data for supplemental Al 2219-T62 spin formed and wrought plate materials following 30-day 3.5% NaCl alternate immersion exposure with an applied stress.

Material Source	Location / Heat Treat	Orient.	Specimen No.	Applied Stress Level ksi	Applied Stress Level % Actual ST YS	Applied Stress Level % MMPDS LT YS	Residual Tensile Strength[1] ksi	Percent Tensile Strength Retained[2]	Residual Strength Ratio[3]	Pass / Fail[4]
Aft Bulkhead	M10 Membrane	ST	M10-4	22.2	50	61.7	35.48	60	1.14	Passed
			M10-5	22.2	50	61.7	33.29	56	1.07	Passed
						Avg.	34.39	58.0	1.11	
			M10-7	33.3	75	92.5	31.80	54	1.03	Passed
			M10-8	33.3	75	92.5	36.71	62	1.18	Passed
						Avg.	34.25	58.0	1.11	
			M10-13	18	40.5	50	34.34	58	1.11	Passed
			M10-14	18	40.5	50	32.32	55	1.04	Passed
						Avg.	33.33	56.5	1.08	
			M10-17	27	60.8	75	33.73	57	1.09	Passed
			M10-18	27	60.8	75	38.03	64	1.23	Passed
						Avg.	35.88	60.5	1.16	
Aft Bulkhead	J1 Pole	ST	J1-4	18	43.0	50	28.11	51	0.88	Passed
			J1-5	18	43.0	50	33.00	60	1.03	Passed
						Avg.	30.56	55.5	0.96	
			J1-1	27	64.5	75	29.58	54	0.92	Passed
			J1-3	27	64.5	75	32.92	60	1.03	Passed
						Avg.	31.25	57.0	0.98	
Aft Bulkhead	J2 Membrane	ST	J2-4	18	41.8	50	37.08	65	1.16	Passed
			J2-6	18	41.8	50	30.97	54	0.97	Passed
						Avg.	34.02	59.5	1.07	
			J2-1	27	62.6	75	31.37	55	0.98	Passed
			J2-3	27	62.6	75	33.17	58	1.04	Passed
						Avg.	32.27	56.5	1.01	
Aft Bulkhead	J3 Rim	ST	J3-4	18	41.1	50	37.65	65	0.97	Passed
			J3-6	18	41.1	50	39.93	69	1.03	Passed
						Avg.	38.79	67.0	1.00	
			J3-1	27	61.6	75	32.68	57	0.85	Passed
			J3-2	27	61.6	75	41.97	73	1.09	Passed
						Avg.	37.32	65.0	0.97	
Plate	Standard	ST	WQ-4	18	41.4	50	34.96	57	1.23	Passed
			WQ-5	18	41.4	50	33.99	55	1.19	Passed
						Avg.	34.47	56.0	1.21	
			WQ-7	27	62.1	75	27.84	45	0.98	Passed
			WQ-8	27	62.1	75	28.63	46	1.01	Passed
						Avg.	28.24	45.5	1.00	
Plate	Modified	ST	GQ-5	18	48.4	50	33.99	57	0.87	Passed
			GQ-6	18	48.4	50	30.65	52	0.78	Passed
						Avg.	32.32	54.5	0.83	
			GQ-8	27	72.6	75	36.71	62	0.94	Passed
			GQ-9	27	72.6	75	37.15	63	0.95	Passed
						Avg.	36.93	62.5	0.95	
CPST Dome	Pole	ST	CP-P4	18	44.8	50	27.93	50	0.85	Passed
			CP-P5	18	44.8	50	19.24	34	0.58	Failed
						Avg.	23.58	42.0	0.72	
			CP-P7	27	67.2	75	26.26	47	0.8	Passed
			CP-P8	27	67.2	75	24.15	43	0.73	Failed
						Avg.	25.21	45.0	0.77	
CPST Dome	Rim	ST	CP-R5	18	48.2	50	29.95	52	0.87	Passed
			CP-R6	18	48.2	50	33.64	59	0.98	Passed
						Avg.	31.80	55.5	0.93	
			CP-R8	27	72.3	75	30.65	54	0.89	Passed
			CP-R9	27	72.3	75	25.21	44	0.73	Failed
						Avg.	27.93	49.0	0.81	

(1) UTS_f = Residual strength of exposed specimen (failure load / original specimen cross-sectional area).

(2) Percent tensile strength retained = UTS_f / UTS_i x 100 where UTS_i = average ultimate tensile strength obtained from baseline tensile tests of non-exposed specimens.

(3) Residual strength ratio = UTS_s/UTS_o where: UTS_s = residual strength of stressed and exposed specimen and UTS_o = averaged residual strength of non-stressed and exposed specimens.

(4) Passed if residual strength ratio ≥0.75, failed if ratio <0.75.

Table 8. Residual tensile strength and percent tensile strength retained for supplemental Al 2219-T62 spin formed and wrought plate materials following 30-day 3.5% NaCl alternate immersion exposure with no applied stress.

Material Source	Location / Heat Treat	Orient.	Specimen No.	Applied Stress Level ksi	Residual Tensile Strength(1) ksi	Percent Tensile Strength Retained(2)
Aft Bulkhead	M10	ST	M10-1	0	38.19	64
			M10-2	0	23.79	40
			Average	**0**	**30.99**	**52**
Aft Bulkhead	J1	ST	J1-7	0	36.59	66
			J1-9	0	27.55	50
			Average	**0**	**32.07**	**58**
Aft Bulkhead	J2	ST	J2-7	0	29.67	52
			J2-9	0	34.07	60
			Average	**0**	**31.87**	**56**
Aft Bulkhead	J3	ST	J3-7	0	36.92	64
			J3-9	0	40.34	69
			Average	**0**	**38.63**	**67**
Plate	Standard	ST	WQ-1	0	28.53	46
			WQ-2	0	28.36	46
			Average	**0**	**28.45**	**46**
Plate	Modified	ST	GQ-2	0	43.63	74
			GQ-3	0	34.5	58
			Average	**0**	**39.07**	**66**
CPST Dome	Pole	ST	CP-P1	0	33.36	59
			CP-P3	0	32.66	58
			Average	**0**	**33.01**	**58**
CPST Dome	Rim	ST	CP-R2	0	35.82	62
			CP-R3	0	33.01	57
			Average	**0**	**34.42**	**60**

(1) UTS_f = Residual strength of exposed specimen (failure load / original specimen cross-sectional area).

(2) Percent tensile strength retained = UTS_f / UTS_i x 100 where UTS_i = average ultimate tensile strength obtained from baseline tensile tests of non-exposed specimens.

Table 9. Residual load carrying ability data from the Phase II SCC testing of spin formed Al 2219-T62 aft bulkhead material following 30-day 3.5% NaCl alternate immersion exposure.

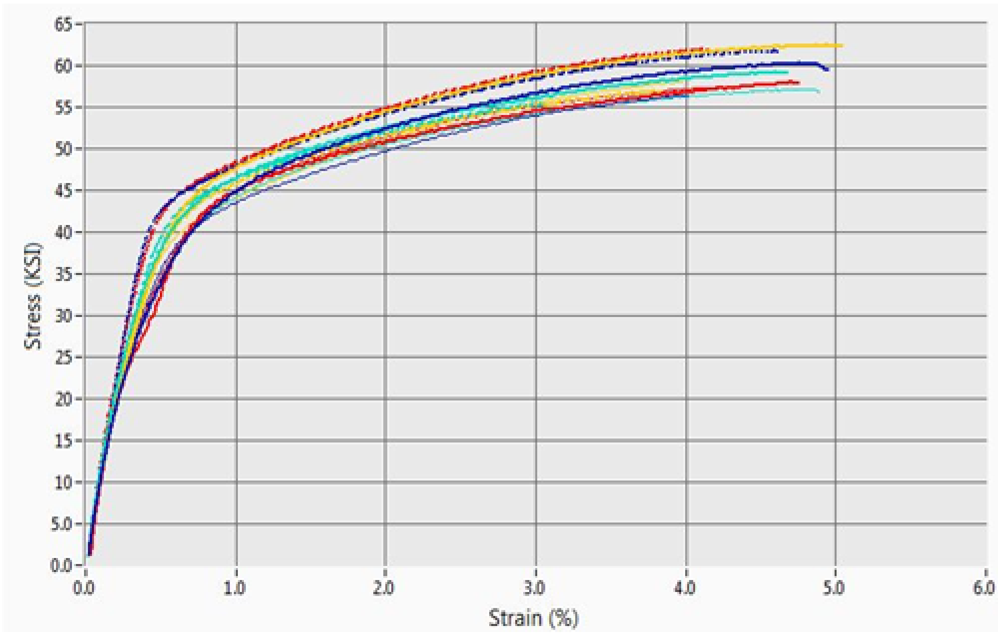
Coupon Blank	Orient.	Baseline UTS, ksi	Baseline YS, ksi	Specimen No.	Applied Stress Level, ksi	Applied Stress Level, % YS	Residual (1) Tensile Strength ksi	Percent (2) Tensile Strength Retained	Residual (3) Strength Ratio	Pass/Fail (4)
M7	ST	57.87	43.20	24	0	0	28.40	49.0	NA	NA
				25	0	0	18.61	32.0	NA	NA
						Avg.	23.51	40.5		
				27	21.60	50	22.51	39.0	0.96	passed
				28	21.60	50	20.97	36.0	0.89	passed
						Avg.	21.74	37.5	0.93	
				-------	32.40	75	-------	-------	-------	-------
				-------	32.40	75	-------	-------	-------	-------
						Avg.	NA	NA	NA	
M8	ST	58.69	43.73	66	0	0	23.25	40.0	NA	NA
				67	0	0	19.44	33.0	NA	NA
						Avg.	21.35	36.5		
				69	21.87	50	16.52	28.0	0.77	passed
				70	21.87	50	32.45	55.0	1.52	passed
						Avg.	24.49	41.5	1.1	
				-------	32.8	75	-------	-------	-------	-------
				-------	32.8	75	-------	-------	-------	-------
						Avg.	NA	NA	NA	
M9	ST	59.86	44.33	108	0	0	26.95	45.0	NA	NA
				109	0	0	19.55	33.0	NA	NA
						Avg.	23.25	39.0		
				110	22.17	50	28.09	47.0	1.21	passed
				112	22.17	50	19.66	33.0	0.85	passed
						Avg.	23.88	40.0	1.03	
				114	33.25	75	24.50	41.0	1.05	passed
				115	33.25	75	27.58	46.0	1.19	passed
						Avg.	26.04	43.5	1.12	
M10	ST	59.65	44.41	150	0	0	18.88	32.0	NA	NA
				151	0	0	19.36	32.0	NA	NA
						Avg.	19.12	32.0		
				153	22.21	50	5.51	9.0	0.29	failed
				154	22.21	50	2.56	4.0	0.13	failed
						Avg.	4.04	6.5	0.21	
				155	33.31	75	20.32	34.0	1.06	passed
				---	---	---	---	---	---	---
						Avg.	20.32	34.0	1.06	

(1) UTS_f = Residual strength of exposed specimen (failure load / original specimen cross-sectional area).

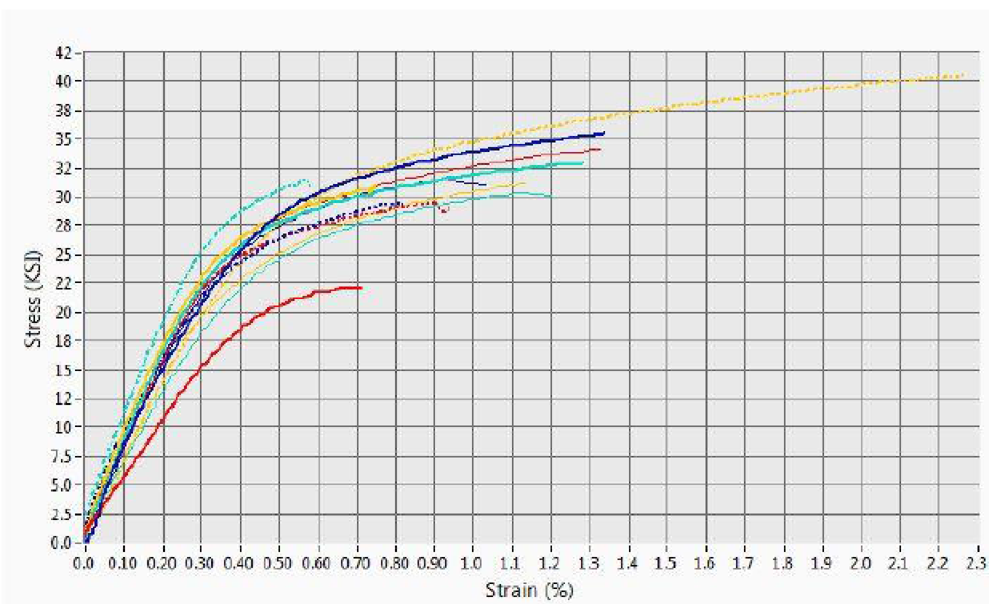
(2) Percent tensile strength retained = UTS_f / UTS_i x 100 where UTS_i = average ultimate tensile strength obtained from baseline tensile tests of non-exposed specimens.

(3) Residual strength ratio = UTS_s/UTS_o where: UTS_s = residual strength of stressed and exposed specimen and UTS_o = averaged residual strength of non-stressed and exposed specimens.

(4) Passed if residual strength ratio ≥0.75, failed if ratio <0.75.

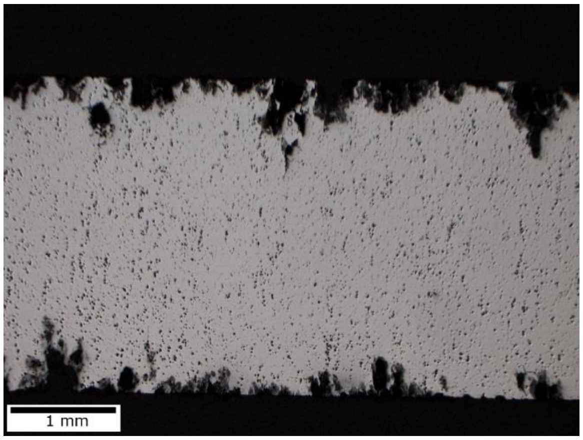


(a) Non-Exposed Specimens

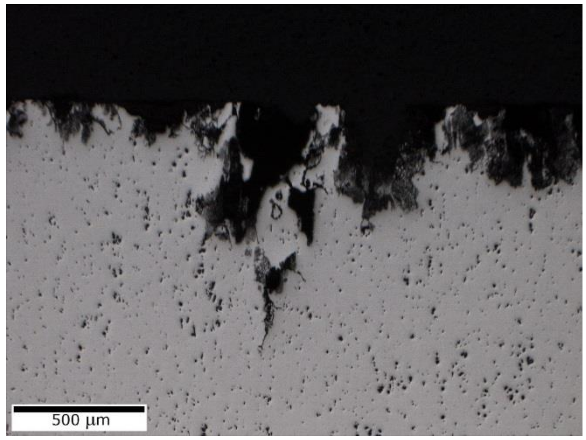


(b) Exposed Specimens

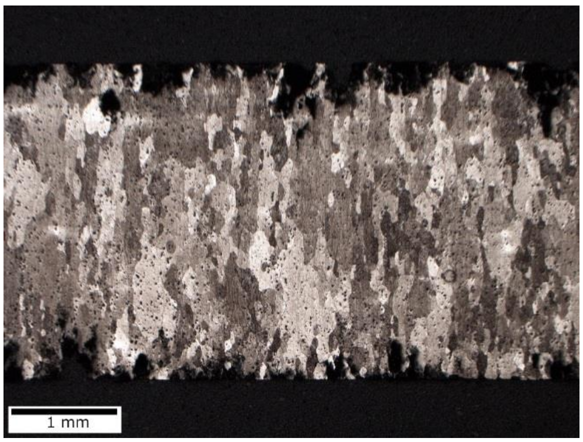
Figure 4. Stress-strain curves for (a) non-exposed specimens and (b) exposed specimens of Al 2219-T62.



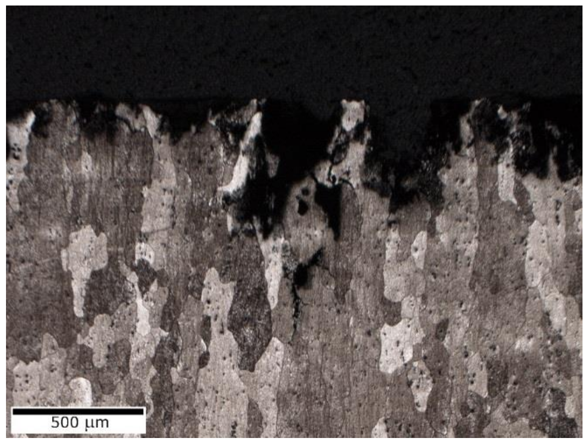
m10-3_unetched_m01_20x.jpg



m10-3_unetched_m02_50x.jpg



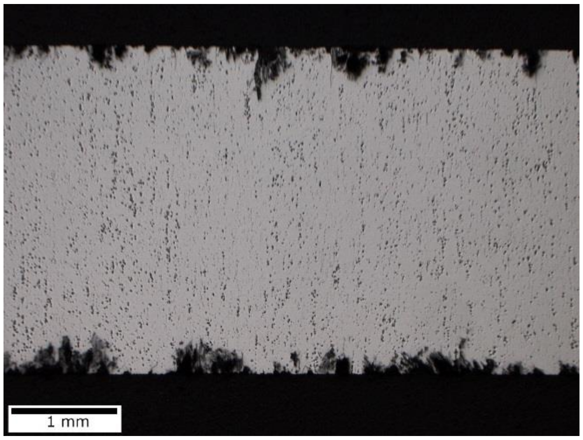
m10-3_etched_m03_20x.jpg



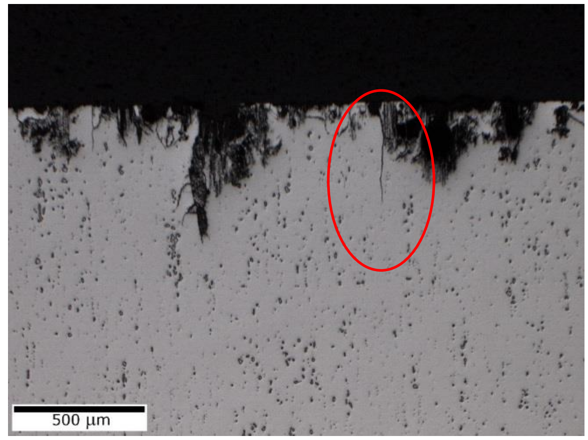
m10-3_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	M10-3
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

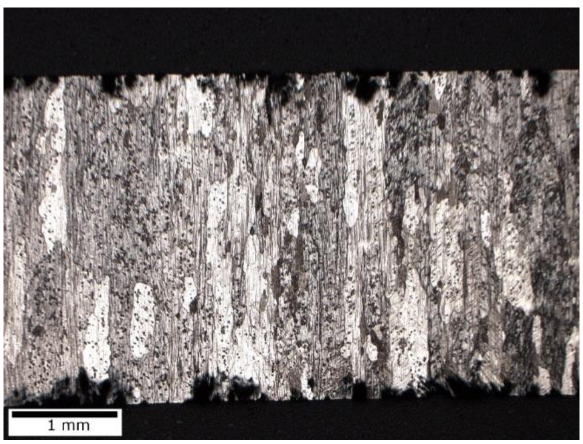
(a) 0% YS



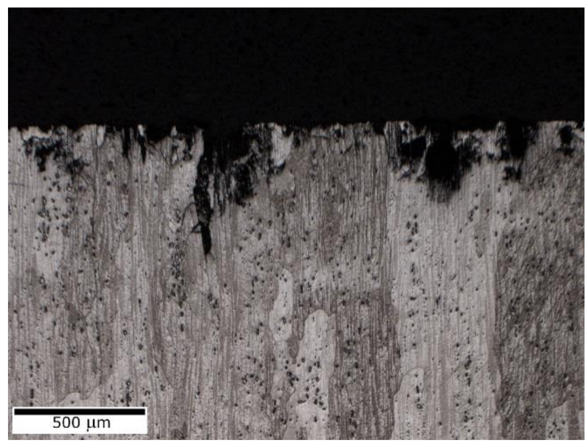
m10-6_unetched_m01_20x.jpg



m10-6_unetched_m02_50x.jpg



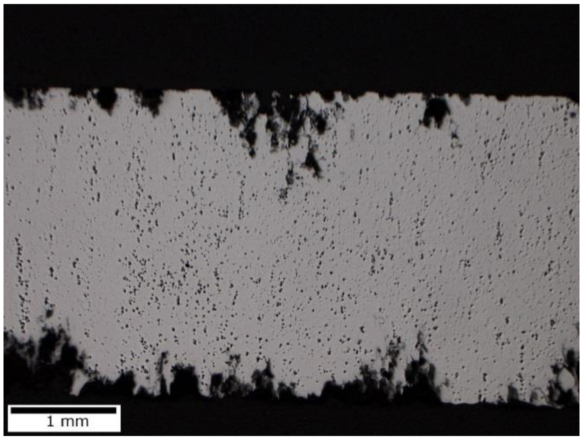
m10-6_etched_m03_20x.jpg



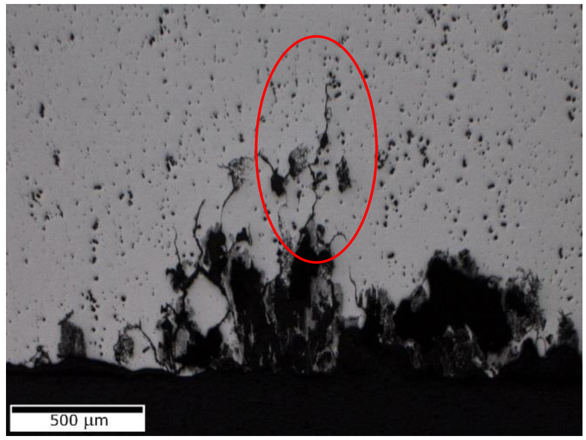
m10-6_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	M10-6
Orientation:	ST
Applied stress (% YS):	50, based on M10 average ST YS
Applied stress (ksi):	22.2
Failed?:	No
SCC?:	Yes; circled in red

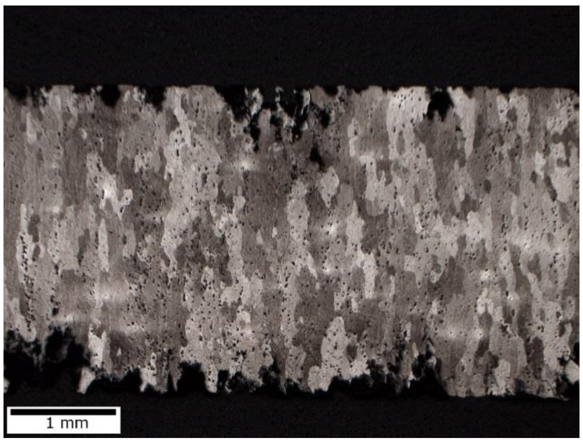
(b) 50% YS (measured)



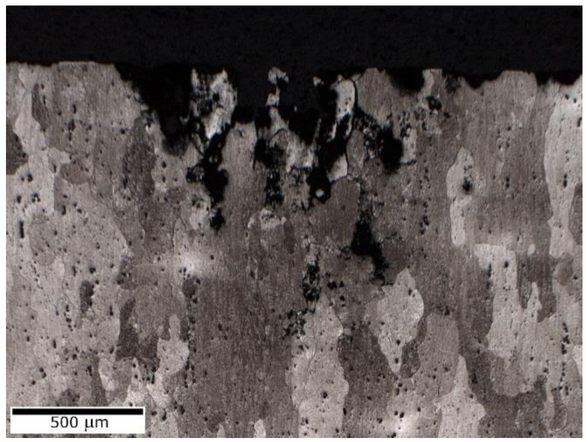
m10-15_unetched_m01_20x.jpg



m10-15_unetched_m02_50x.jpg



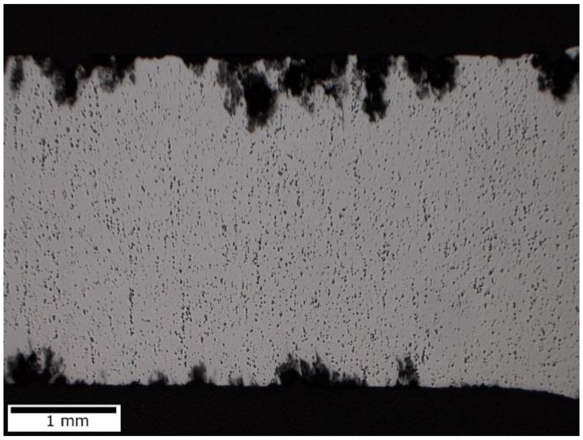
m10-15_etched_m03_20x.jpg



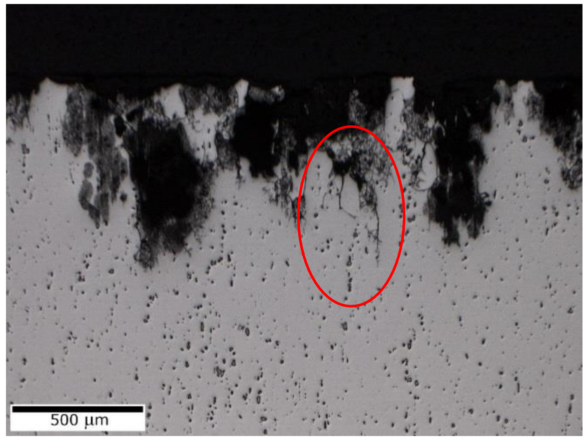
m10-15_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	M10-15
Orientation:	ST
Applied stress (% YS):	50, based on MMPDS LT YS
Applied stress (ksi):	18
Failed?:	No
SCC?:	Yes; circled in red

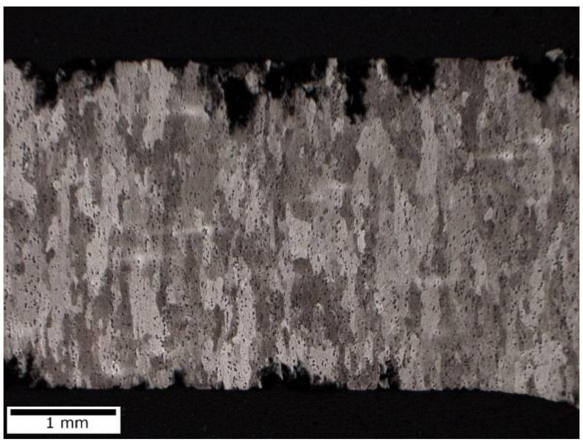
(c) 50% YS (MMPDS)



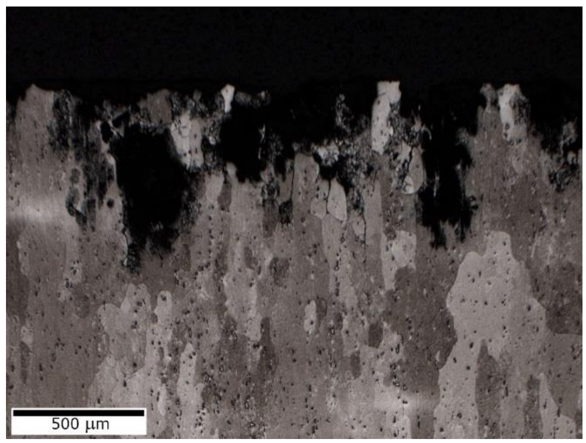
m10-9_unetched_m01_20x.jpg



m10-9_unetched_m02_50x.jpg



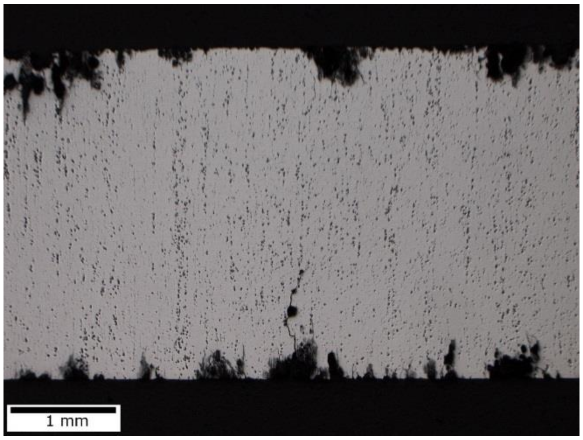
m10-9_etched_m03_20x.jpg



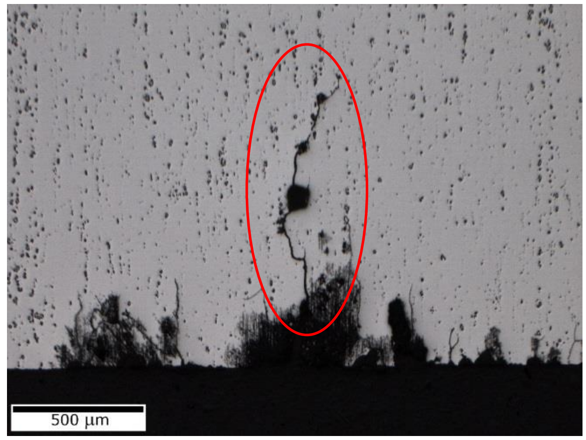
m10-9_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	M10-9
Orientation:	ST
Applied stress (% YS):	75, based on M10 average ST YS
Applied stress (ksi):	33.3
Failed?:	No
SCC?:	Yes; circled in red

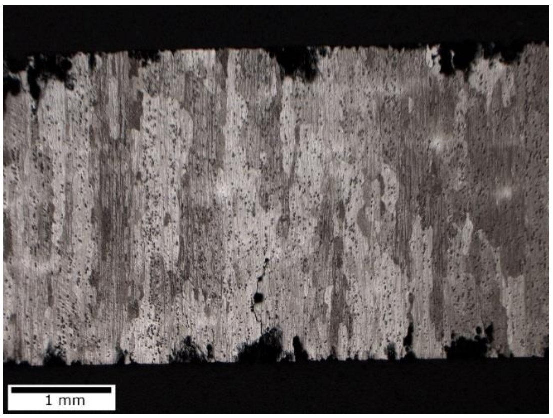
(d) 75% YS (measured)



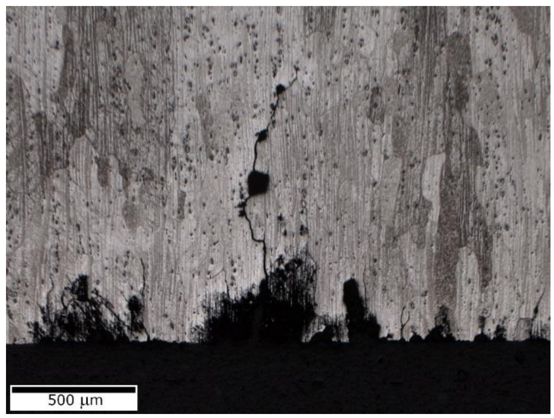
m10-16_unetched_m01_20x.jpg



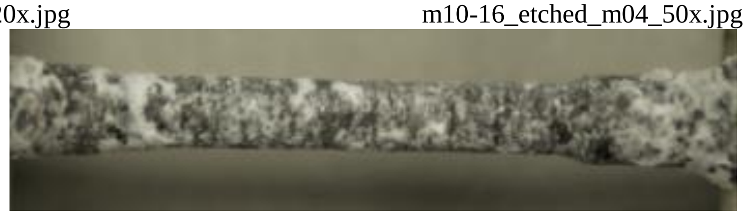
m10-16_unetched_m02_50x.jpg



m10-16_etched_m03_20x.jpg



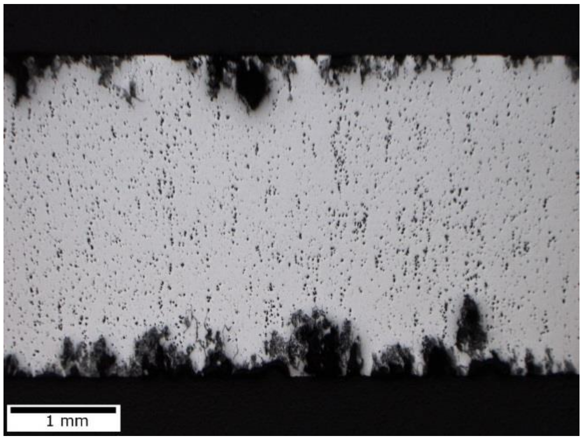
m10-16_etched_m04_50x.jpg



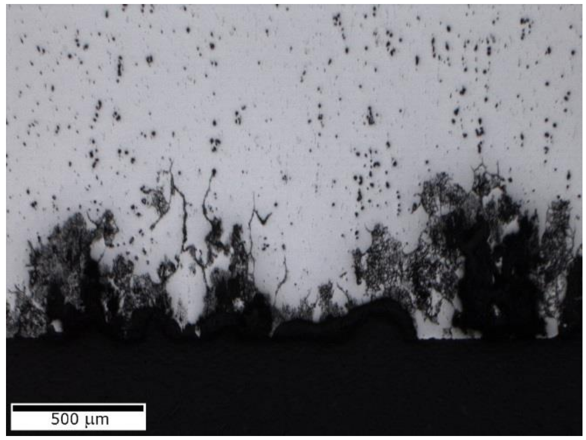
Coupon blank:	M10
Specimen No.:	M10-16
Orientation:	ST
Applied stress (% YS):	75, based on MMPDS LT YS
Applied stress (ksi):	27
Failed?:	No
SCC?:	Yes; circled in red

(e) 75% YS (MMPDS)

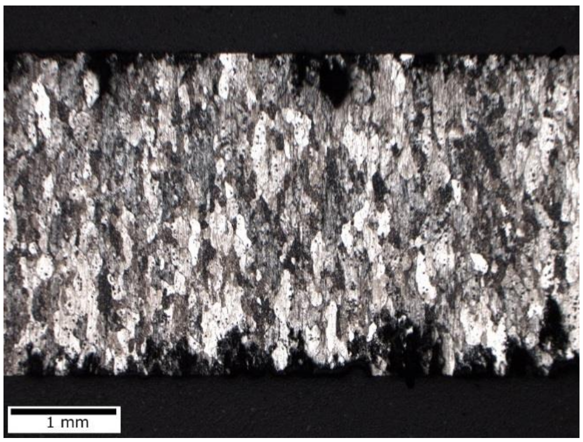
Figure 5. ***Photomicrographs of SCC specimens from aft bulkhead coupon blank M10 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS (measured); (c) 50% YS (MMPDS); (d) 75% YS (measured); and (e) 75% YS (MMPDS).***



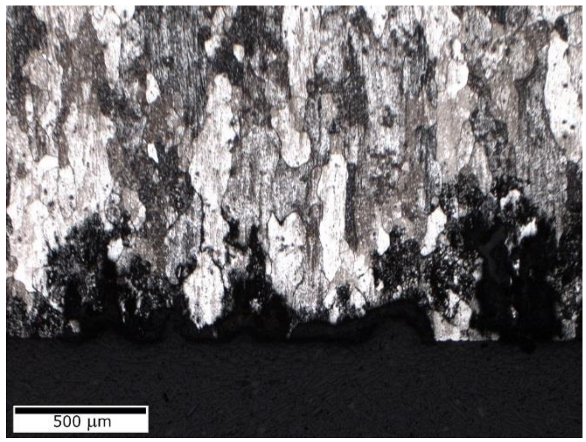
j1-8_unetched_m01_20x.jpg



j1-8_unetched_m02_50x.jpg



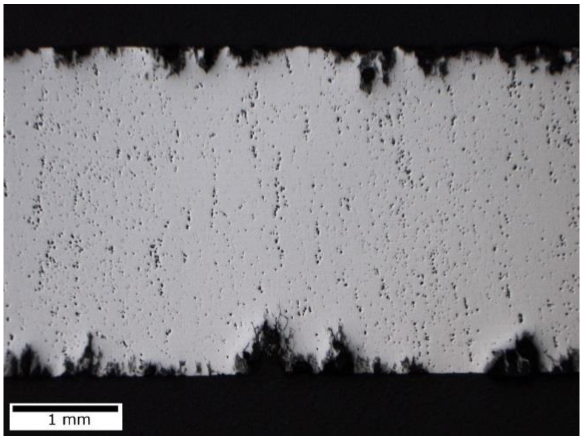
j1-8_etched_m03_20x.jpg



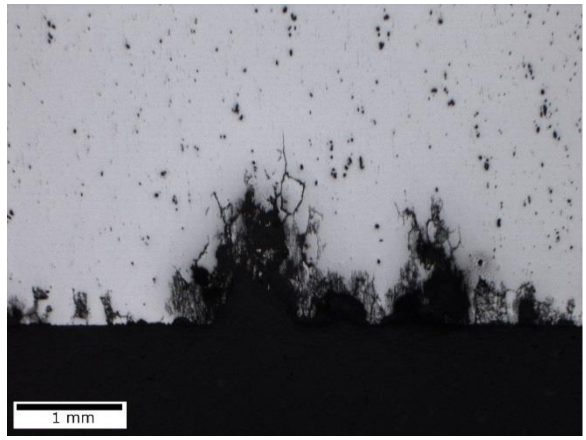
j1-8_etched_m04_50x.jpg

Coupon blank:	J1
Specimen No.:	J1-8
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

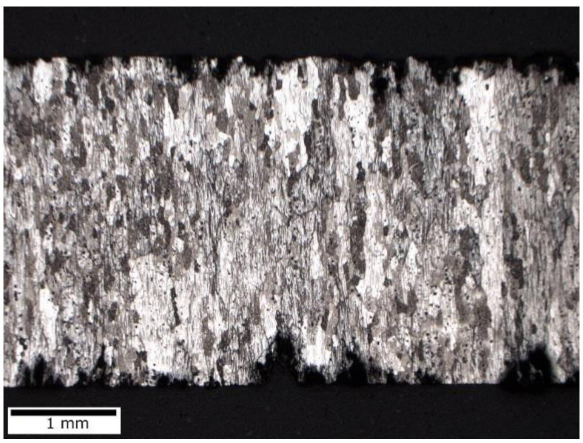
(a) 0% YS



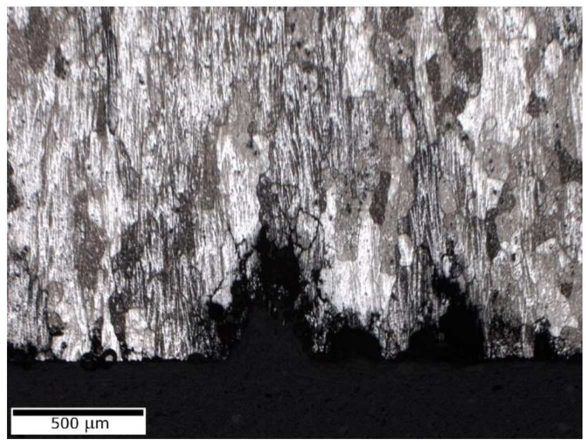
j1-6_unetched_m01_20x.jpg



j1-6_unetched_m02_50x.jpg



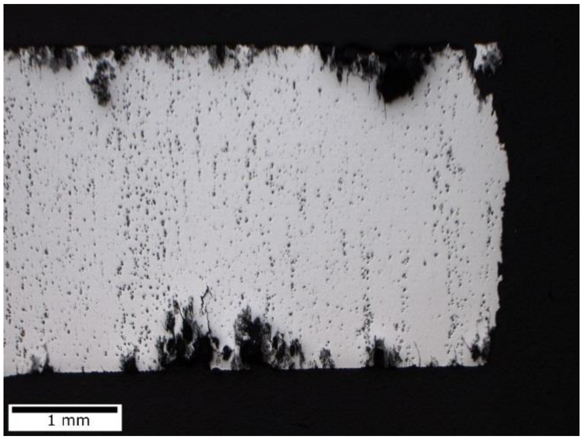
j1-6_etched_m03_20x.jpg



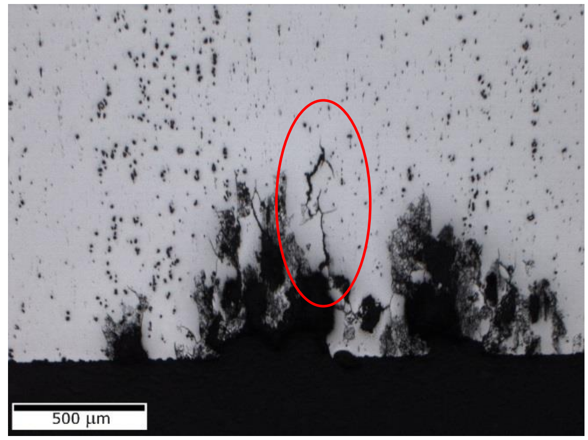
j1-6_etched_m04_50x.jpg

Coupon blank:	J1
Specimen No.:	J1-6
Orientation:	ST
Applied stress (% YS):	50, based on MMPDS LT YS
Applied stress (ksi):	18
Failed?:	No
SCC?:	No

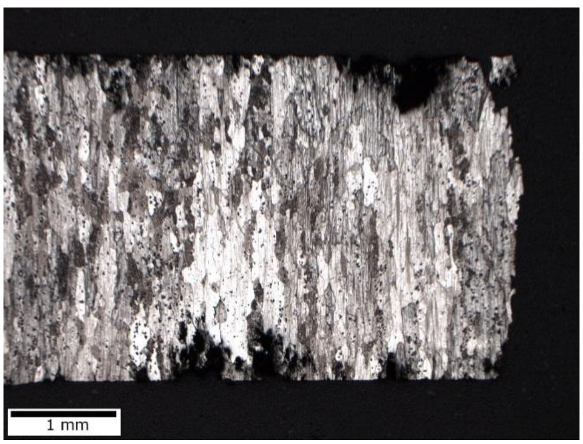
(b) 50% YS



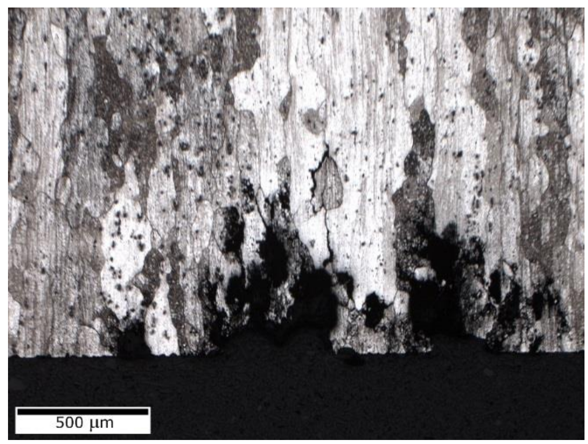
j1-2_unetched_m01_20x.jpg



j1-2_unetched_m02_50x.jpg



j1-2_etched_m03_20x.jpg

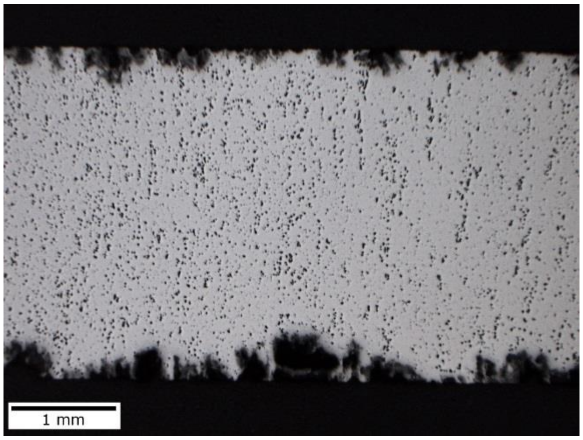


j1-2_etched_m04_50x.jpg

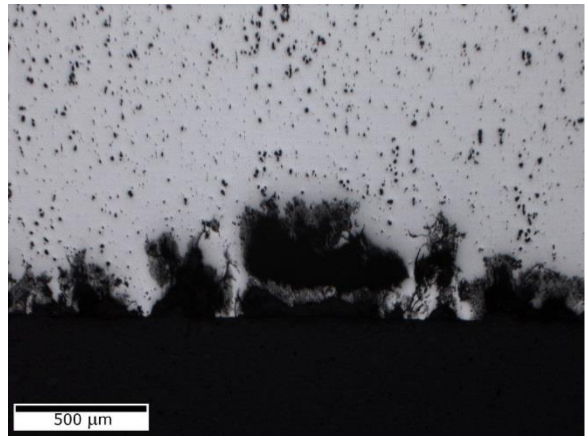
Coupon blank:	J1
Specimen No.:	J1-2
Orientation:	ST
Applied stress (% YS):	75, based on MMPDS LT YS
Applied stress (ksi):	27
Failed?:	No
SCC?:	Yes; circled in red

(c) 75% YS

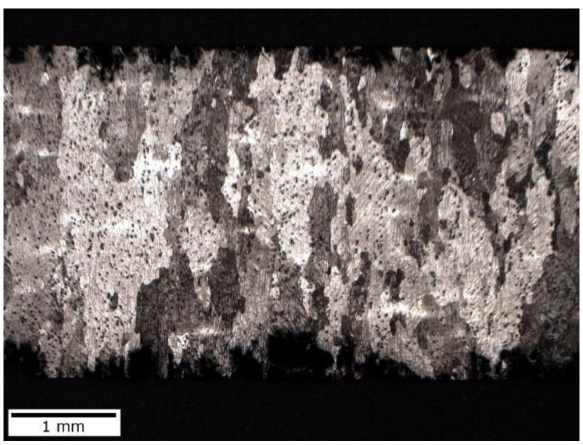
Figure 6. ***Photomicrographs of SCC specimens from aft bulkhead coupon blank J1 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; and (c) 75% YS.***



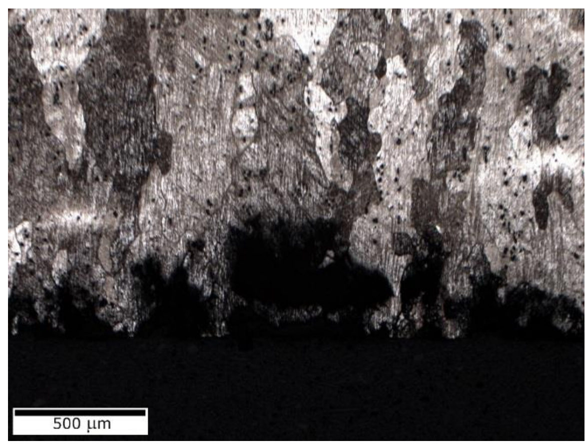
j2-8_unetched_m01_20x.jpg



j2-8_unetched_m02_50x.jpg



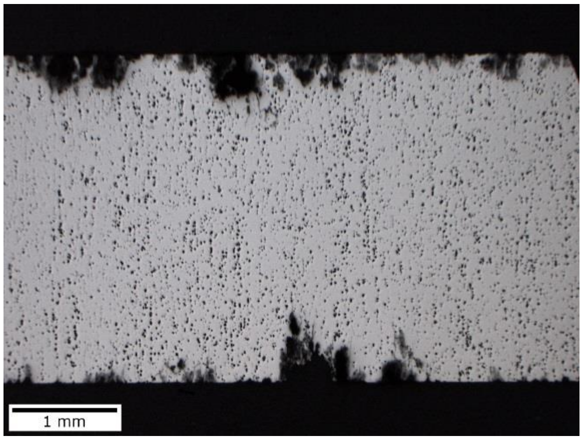
j2-8_etched_m03_20x.jpg



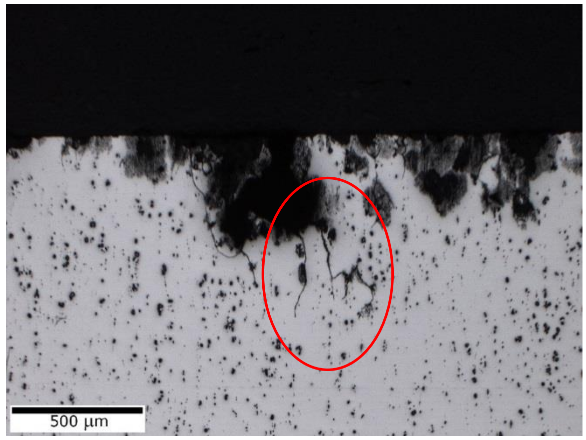
j2-8_etched_m04_50x.jpg

Coupon blank:	J2
Specimen No.:	J2-8
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

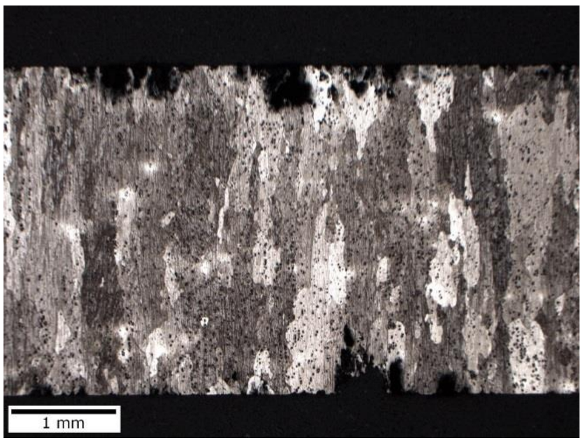
(a) 0% YS



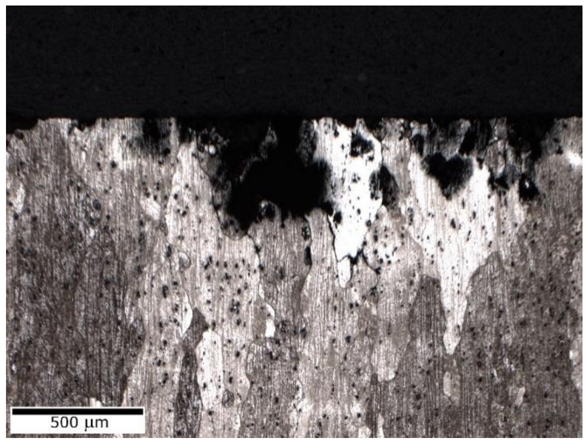
j2-5_unetched_m01_20x.jpg



j2-5_unetched_m02_50x.jpg



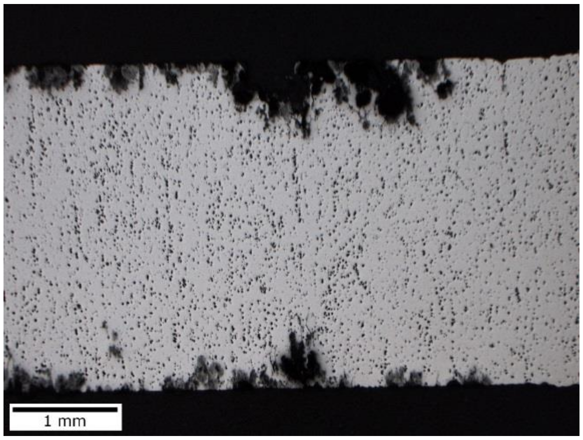
j2-5_etched_m03_20x.jpg



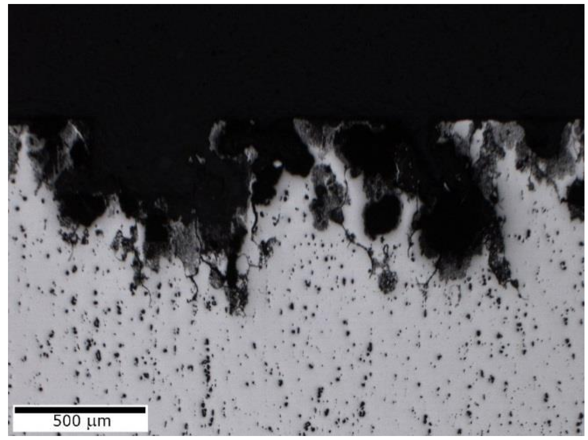
j2-5_etched_m04_50x.jpg

Coupon blank:	J2
Specimen No.:	J2-5
Orientation:	ST
Applied stress (% YS):	50, based on MMPDS LT YS
Applied stress (ksi):	18
Failed?:	No
SCC?:	Yes; circled in red

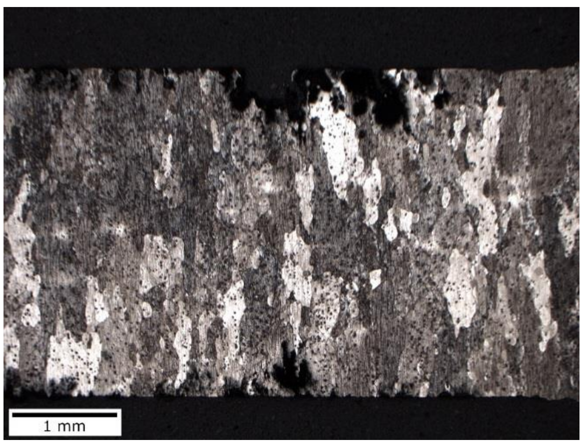
(b) 50% YS



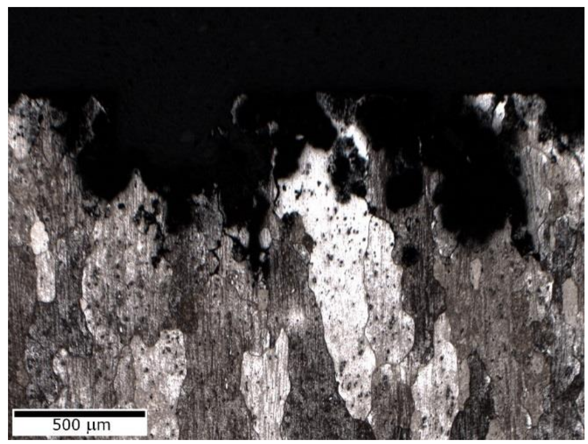
j2-2_unetched_m01_20x.jpg



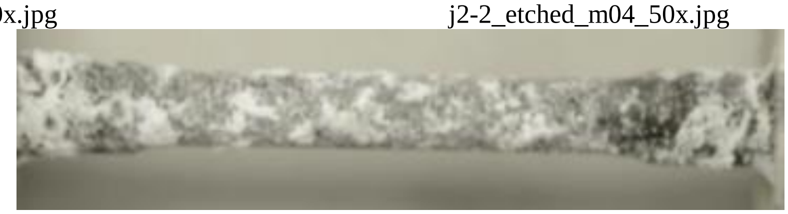
j2-2_unetched_m02_50x.jpg



j2-2_etched_m03_20x.jpg



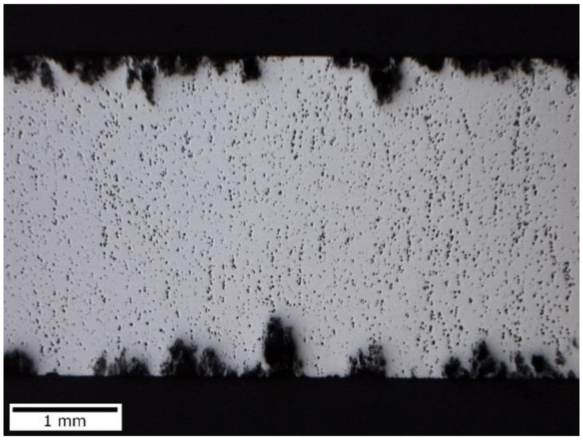
j2-2_etched_m04_50x.jpg



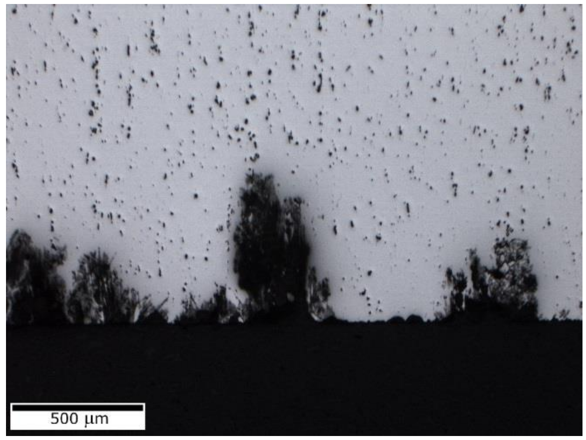
Coupon blank:	J2
Specimen No.:	J2-2
Orientation:	ST
Applied stress (% YS):	75, based on MMPDS LT YS
Applied stress (ksi):	27
Failed?:	No
SCC?:	No

(c) 75% YS

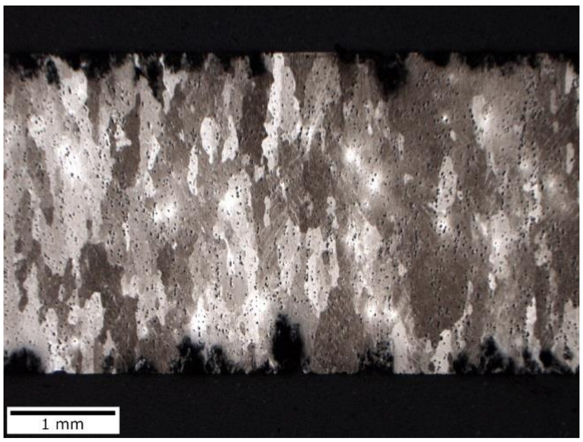
Figure 7. ***Photomicrographs of SCC specimens from aft bulkhead coupon blank J2 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; and (c) 75% YS.***



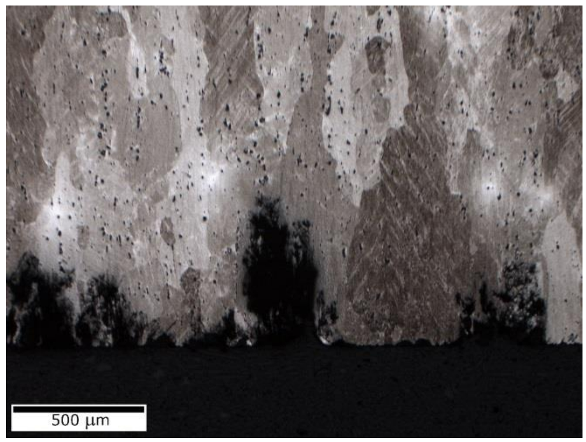
j3-8_unetched_m01_20x.jpg



j3-8_unetched_m02_50x.jpg



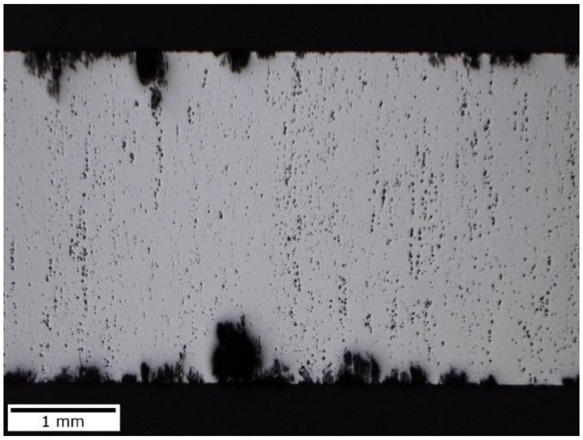
j3-8_etched_m03_20x.jpg



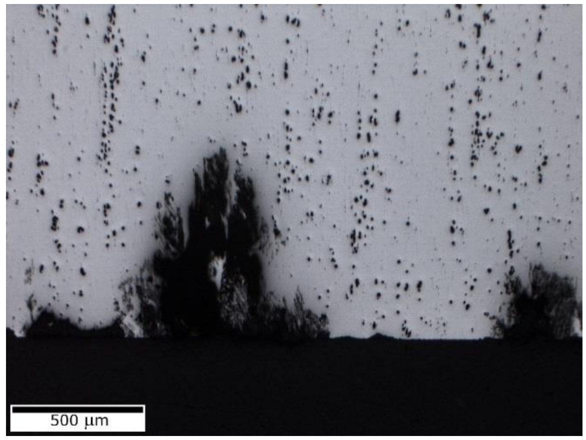
j3-8_etched_m04_50x.jpg

Coupon blank:	J3
Specimen No.:	J3-8
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

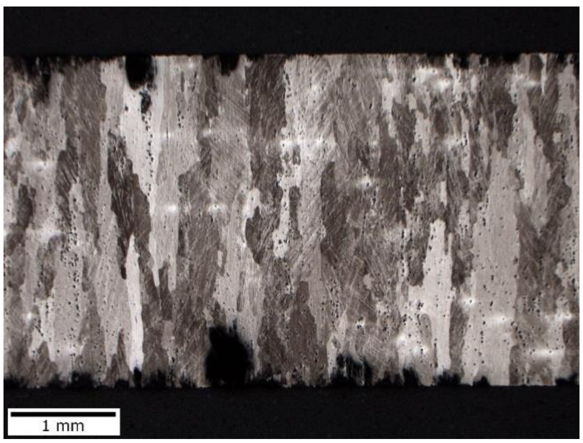
(a) 0% YS



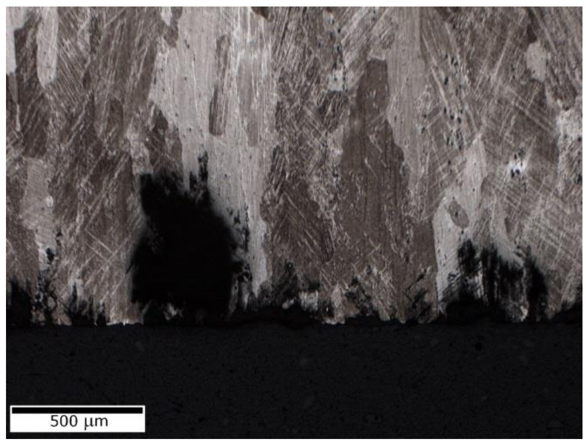
j3-5_unetched_m01_20x.jpg



j3-5_unetched_m02_50x.jpg



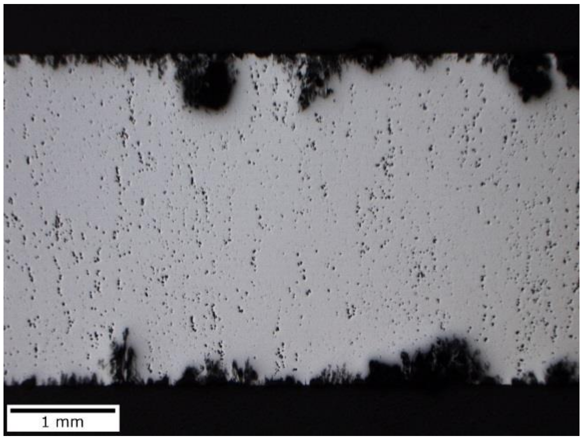
j3-5_etched_m03_20x.jpg



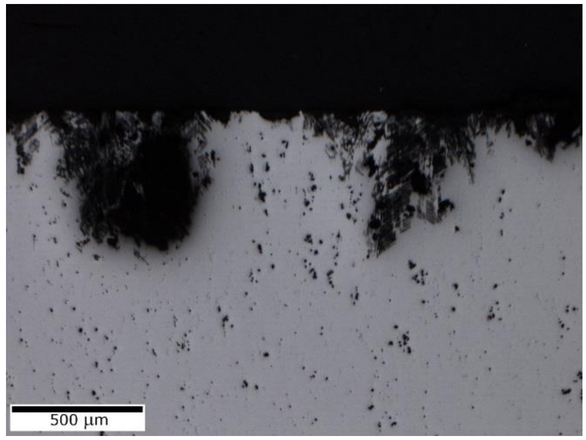
j3-5_etched_m04_50x.jpg

Coupon blank:	J3
Specimen No.:	J3-5
Orientation:	ST
Applied stress (% YS):	50, based on MMPDS LT YS
Applied stress (ksi):	18
Failed?:	No
SCC?:	No

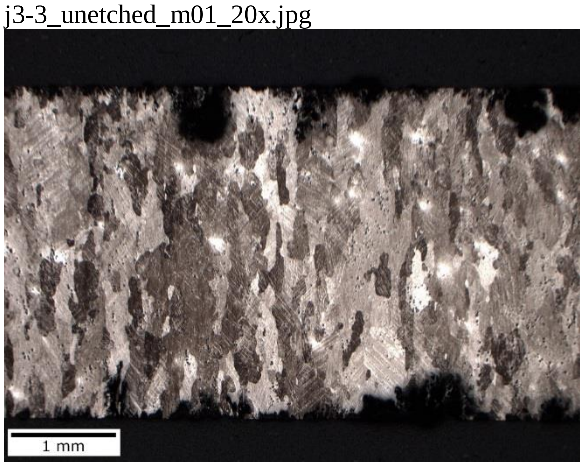
(b) 50% YS



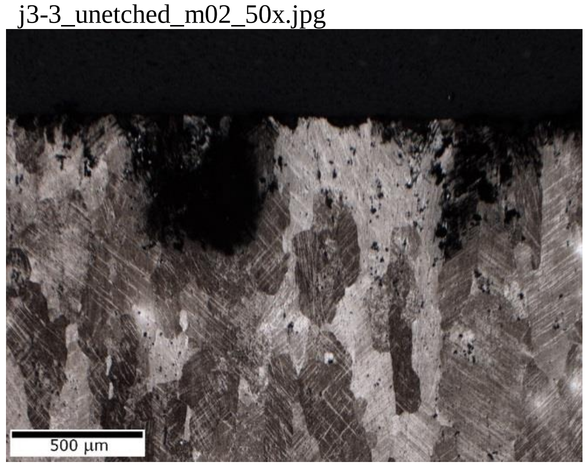
j3-3_unetched_m01_20x.jpg



j3-3_unetched_m02_50x.jpg



j3-3_etched_m03_20x.jpg

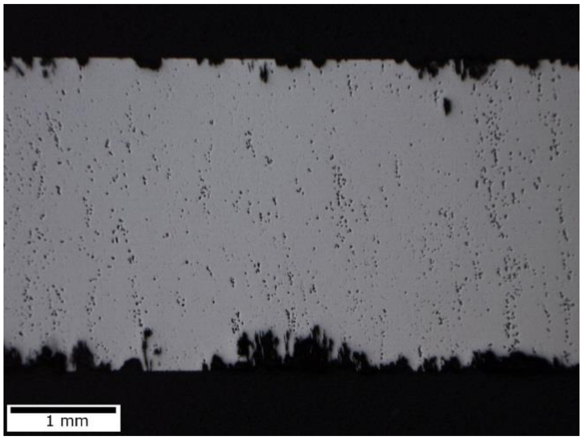


j3-3_etched_m04_50x.jpg

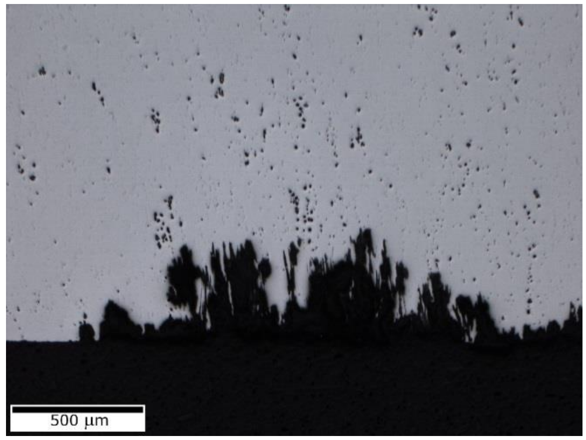
Coupon blank:	J3
Specimen No.:	J3-3
Orientation:	ST
Applied stress (% YS):	75, based on MMPDS LT YS
Applied stress (ksi):	27
Failed?:	No
SCC?:	No

(c) 75% YS

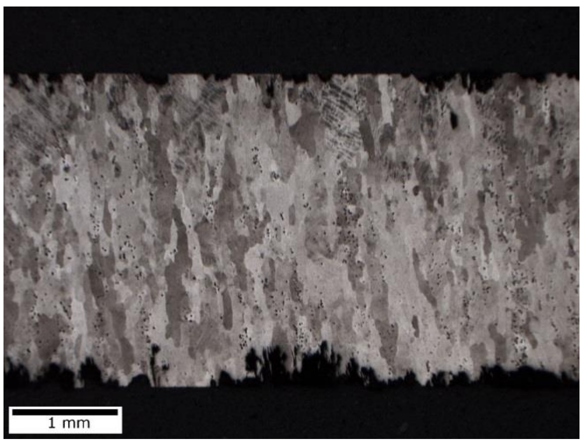
Figure 8. Photomicrographs of SCC specimens from aft bulkhead coupon blank J3 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; and (c) 75% YS.



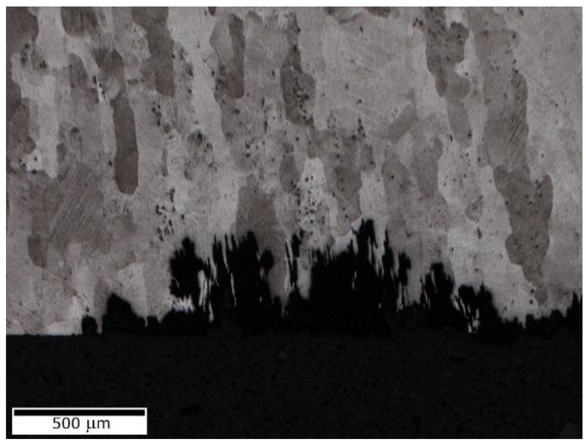
wq-3_unetched_m01_20x.jpg



wq-3_unetched_m02_50x.jpg



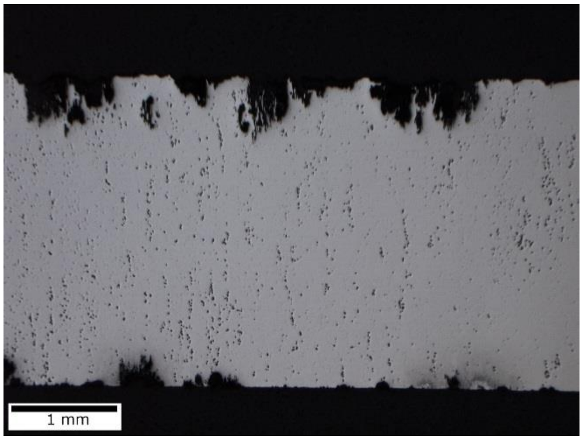
wq-3_etched_m03_20x.jpg



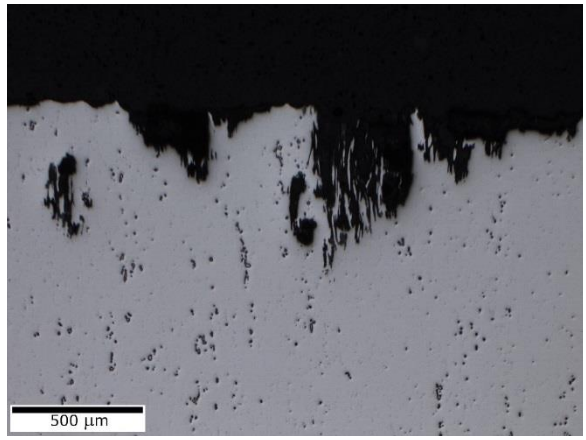
wq-3_etched_m04_50x.jpg

Coupon blank:	Standard plate
Specimen No.:	WQ-3
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

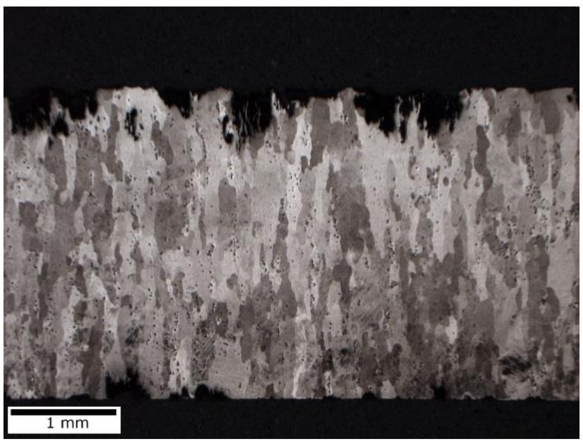
(a) 0% YS



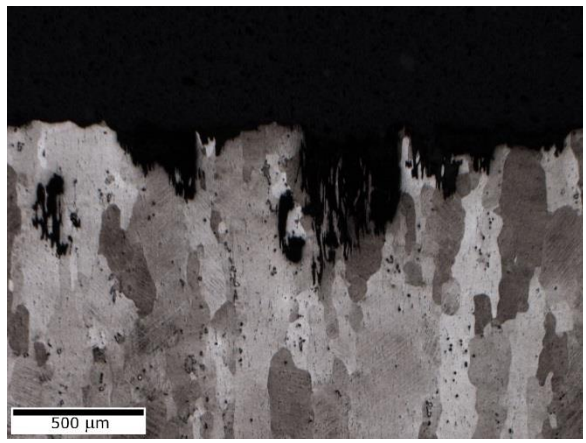
wq-6_unetched_m01_20x.jpg



wq-6_unetched_m02_50x.jpg



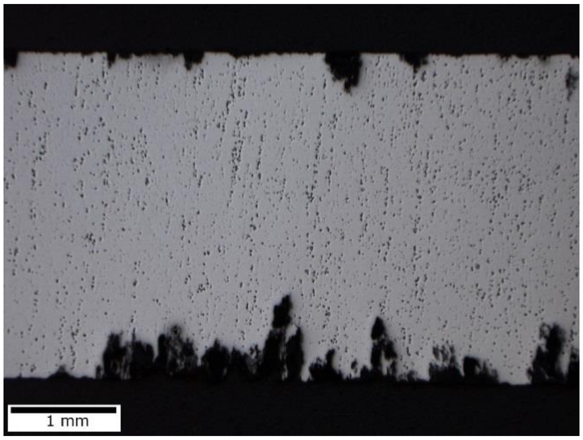
wq-6_etched_m03_20x.jpg



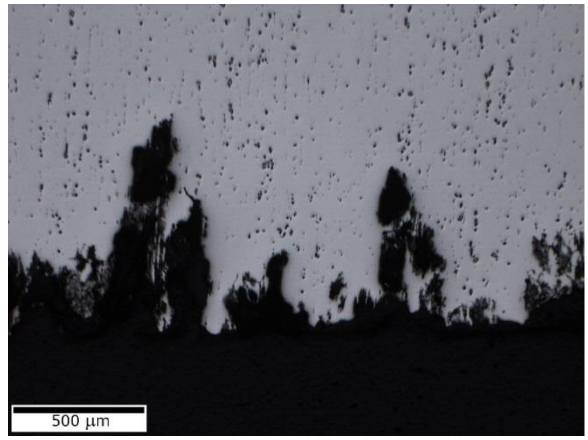
wq-6_etched_m04_50x.jpg

Coupon blank:	Standard plate
Specimen No.:	WQ-6
Orientation:	ST
Applied stress (% YS):	50, based on MMPDS LT YS
Applied stress (ksi):	18
Failed?:	No
SCC?:	No

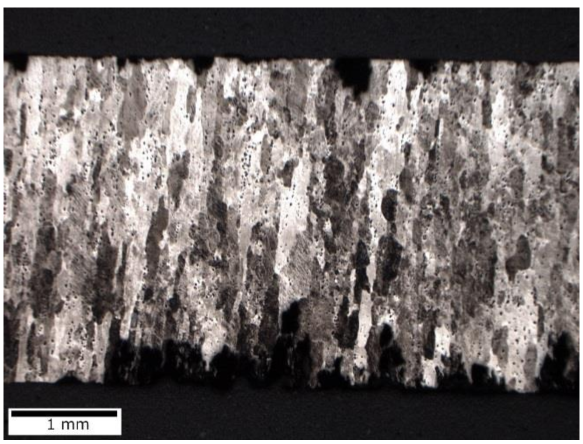
(b) 50% YS



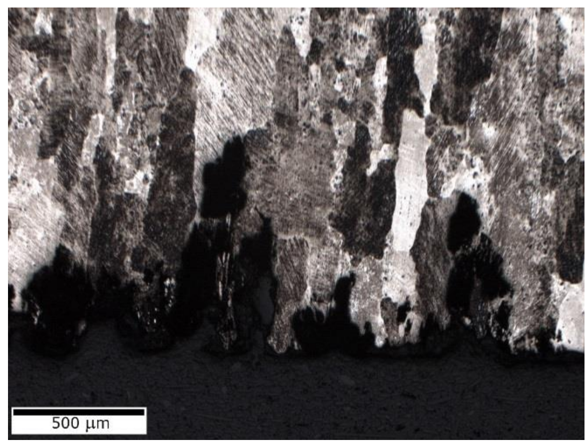
wq-9_unetched_m01_20x.jpg



wq-9_unetched_m02_50x.jpg



wq-9_etched_m03_20x.jpg

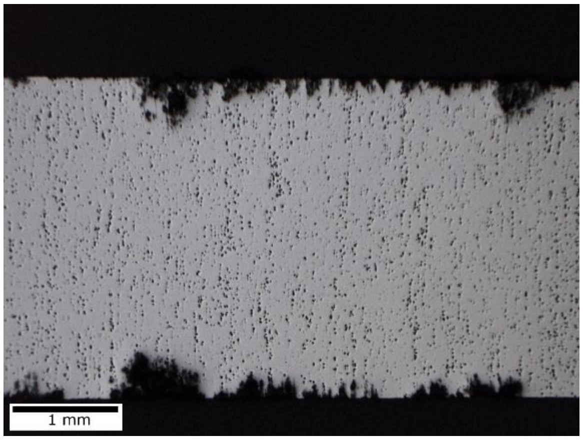


wq-9_etched_m04_50x.jpg

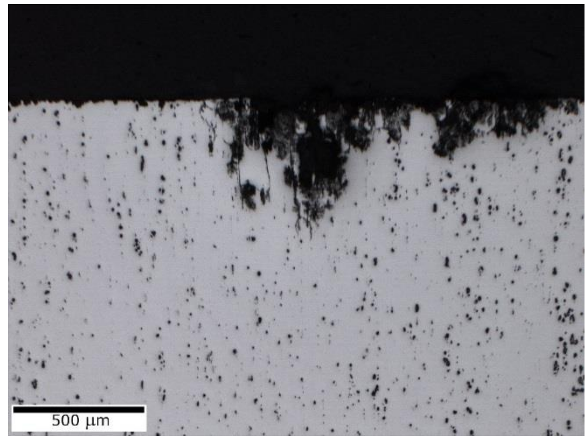
Coupon blank:	Standard plate
Specimen No.:	WQ-9
Orientation:	ST
Applied stress (% YS):	75, based on MMPDS LT YS
Applied stress (ksi):	27
Failed?:	No
SCC?:	No

(c) 75% YS

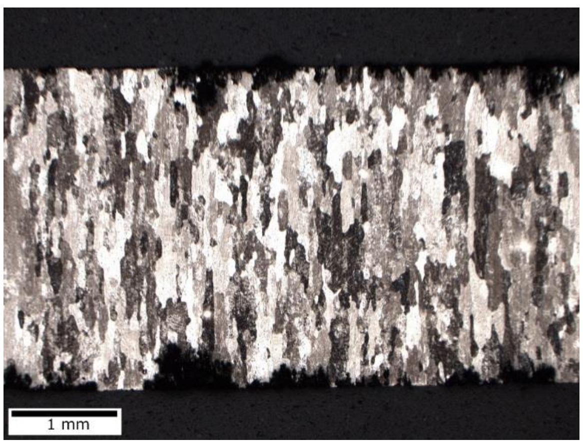
Figure 9. ***Photomicrographs of SCC specimens from standard plate following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; and (c) 75% YS.***



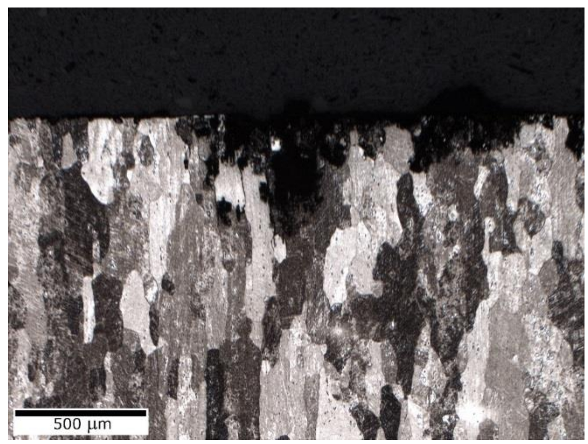
gq-1_unetched_m01_20x.jpg



gq-1_unetched_m02_50x.jpg



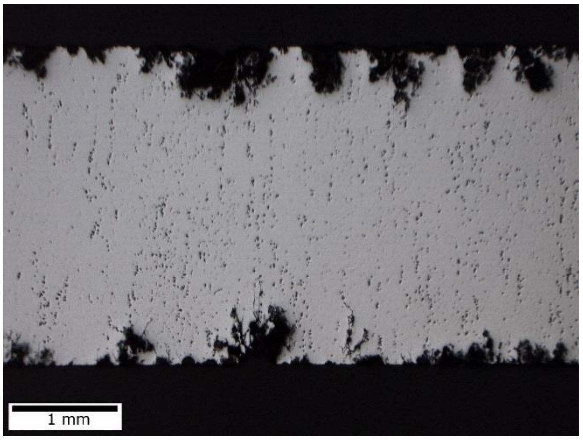
gq-1_etched_m03_20x.jpg



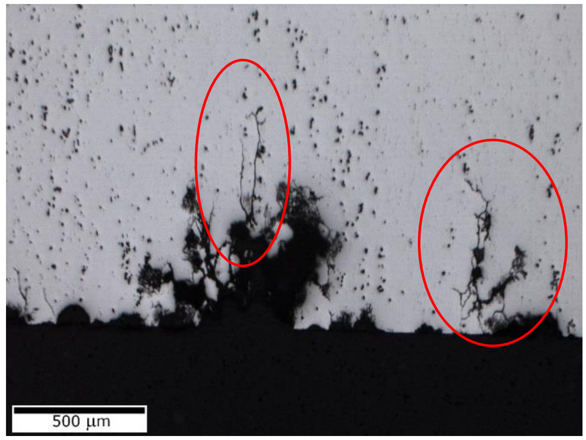
gq-1_etched_m04_50x.jpg

Coupon blank:	Modified plate
Specimen No.:	GQ-1
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

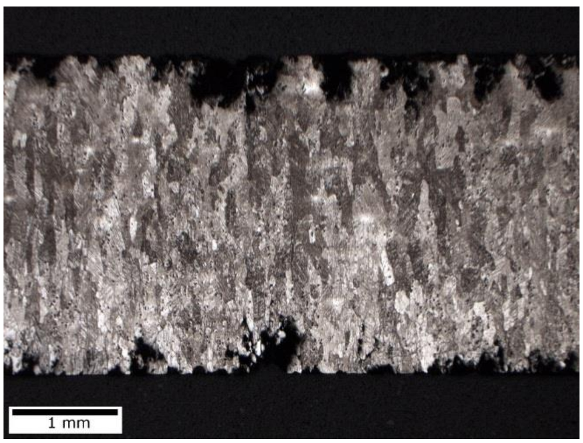
(a) 0% YS



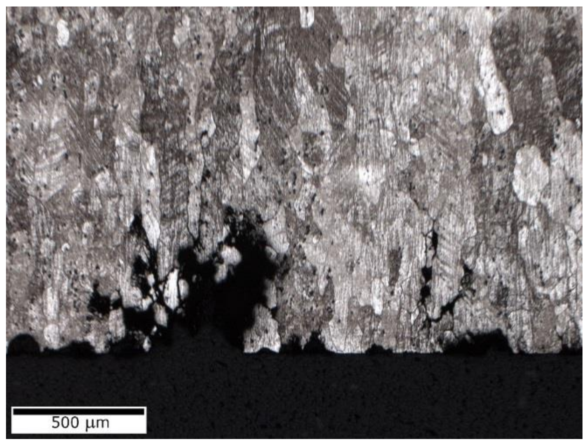
gq-4_unetched_m01_20x.jpg



gq-4_unetched_m02_50x.jpg



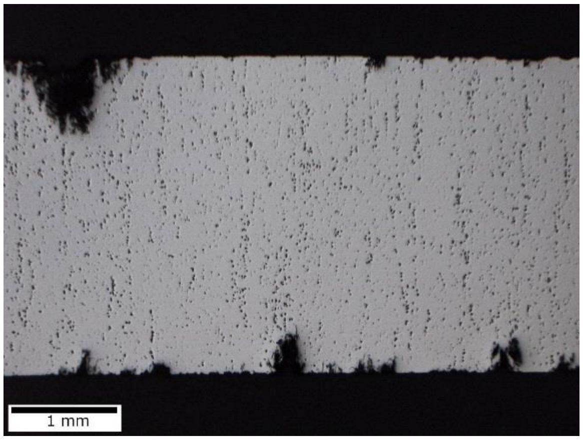
gq-4_etched_m03_20x.jpg



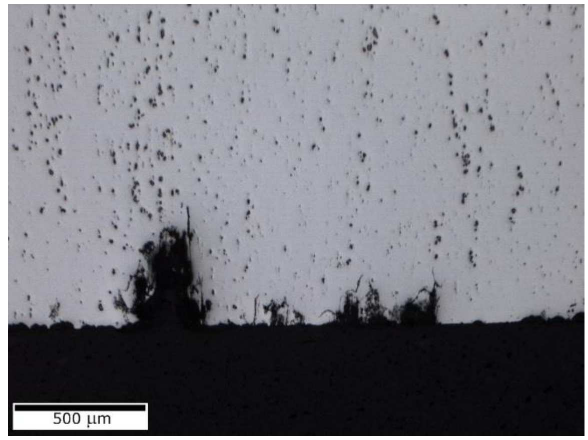
gq-4_etched_m04_50x.jpg

Coupon blank:	Modified plate
Specimen No.:	GQ-4
Orientation:	ST
Applied stress (% YS):	50, based on MMPDS LT YS
Applied stress (ksi):	18
Failed?:	No
SCC?:	Yes; encircled in red

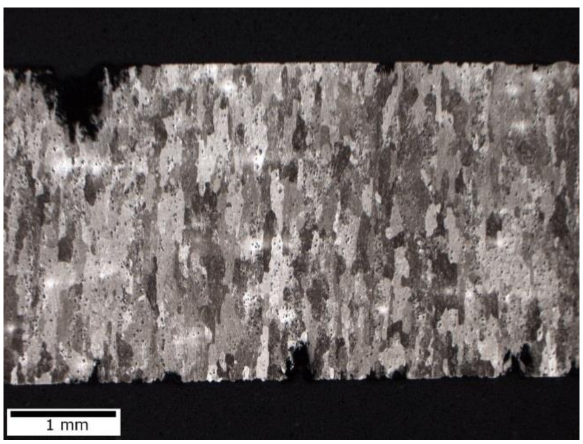
(b) 50% YS



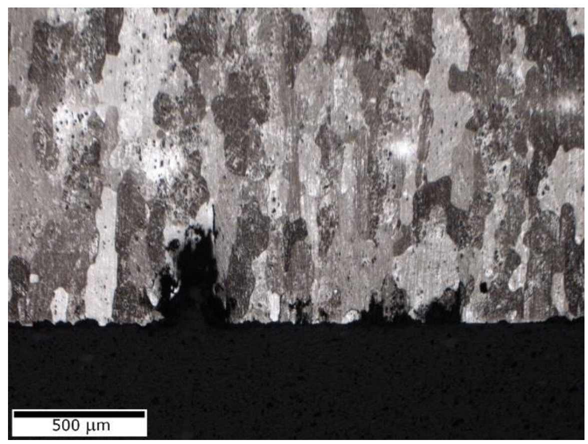
gq-7_unetched_m01_20x.jpg



gq-7_unetched_m02_50x.jpg



gq-7_etched_m03_20x.jpg

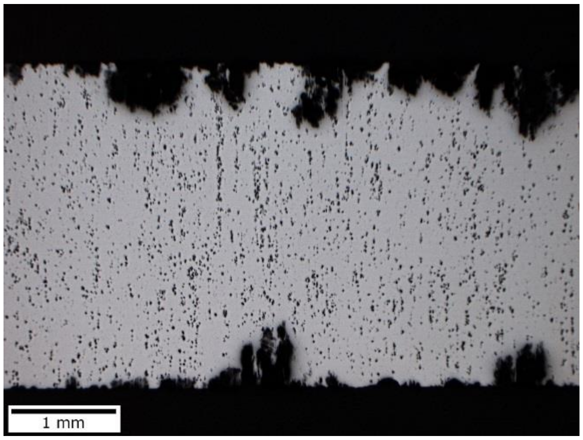


gq-7_etched_m04_50x.jpg

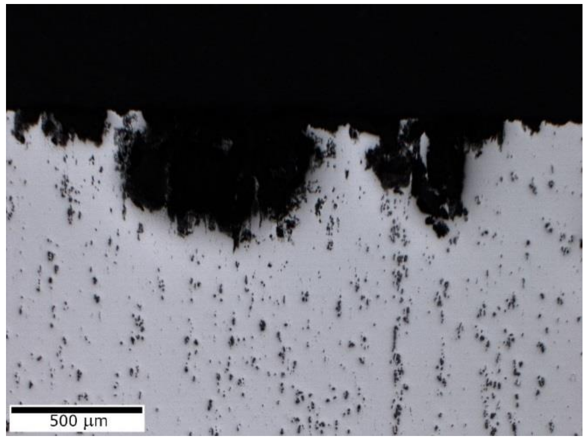
Coupon blank:	Modified plate
Specimen No.:	GQ-7
Orientation:	ST
Applied stress (% YS):	75, based on MMPDS LT YS
Applied stress (ksi):	27
Failed?:	No
SCC?:	No

(c) 75% YS

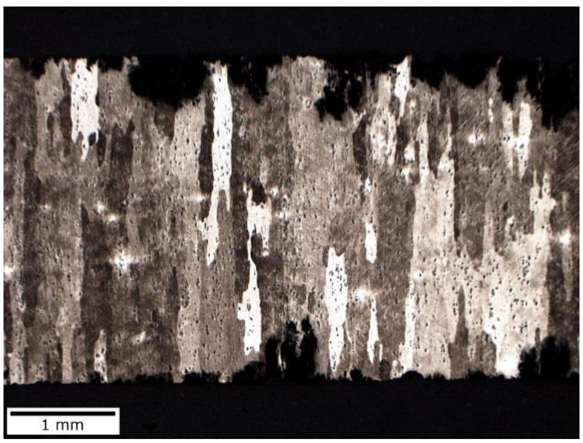
Figure 10. Photomicrographs of SCC specimens from modified plate following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; and (c) 75% YS.



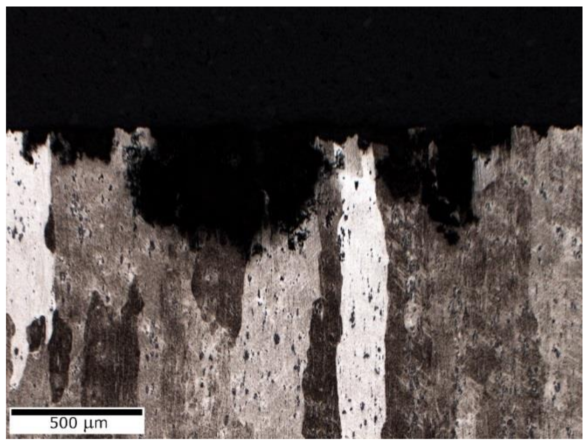
cp-p2_unetched_m01_20x.jpg



cp-p2_unetched_m02_50x.jpg



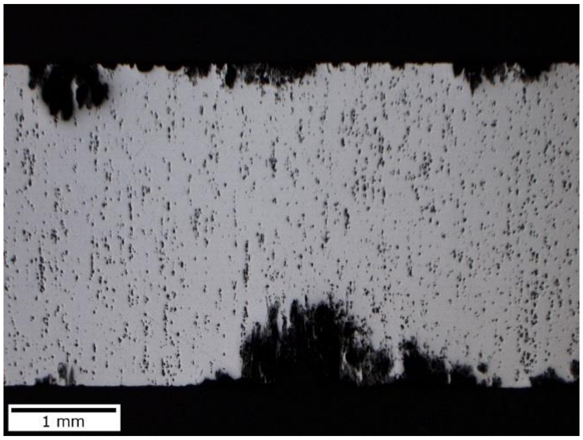
cp-p2_etched_m03_20x.jpg



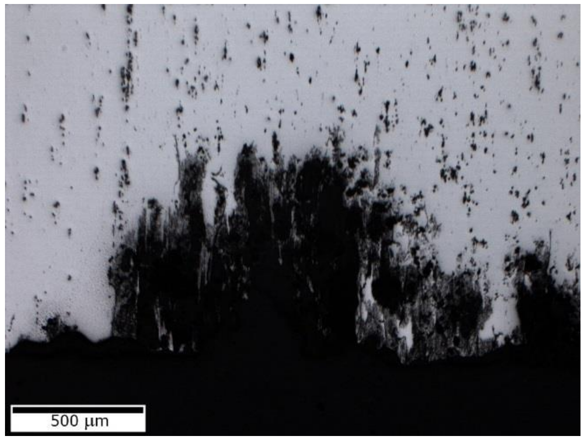
cp-p2_etched_m04_50x.jpg

Coupon blank:	CPST dome; pole region
Specimen No.:	CP-P2
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

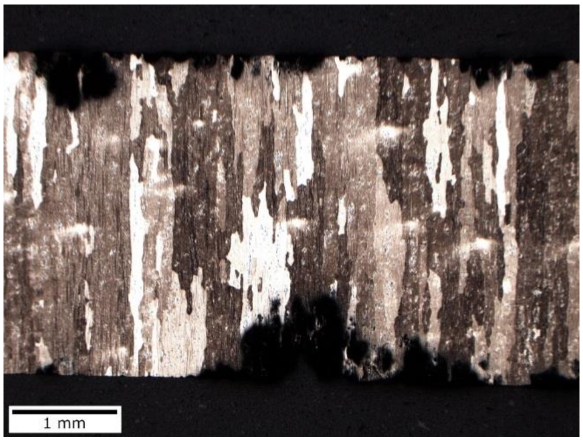
(a) 0% YS



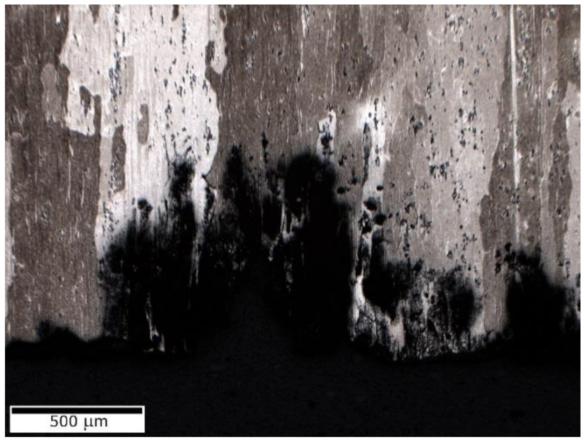
cp-p6_unetched_m01_20x.jpg



cp-p6_unetched_m02_50x.jpg



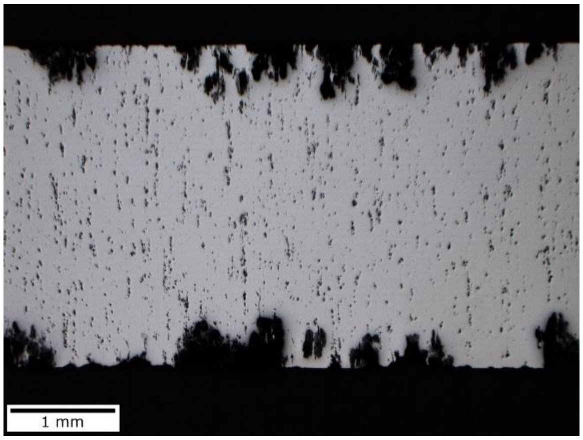
cp-p6_etched_m03_20x.jpg



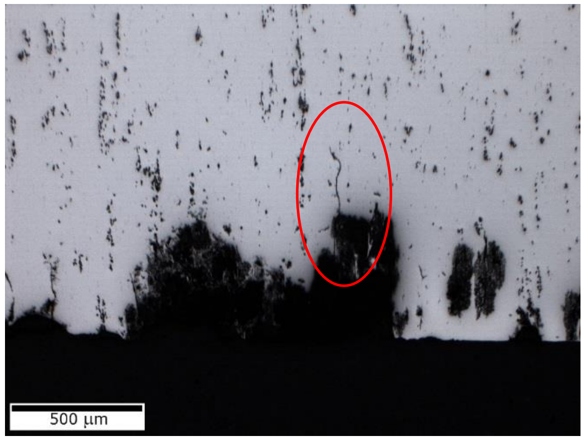
cp-p6_etched_m04_50x.jpg

Coupon blank:	CPST dome; pole region
Specimen No.:	CP-P6
Orientation:	ST
Applied stress (% YS):	50, based on MMPDS LT YS
Applied stress (ksi):	18
Failed?:	No
SCC?:	No

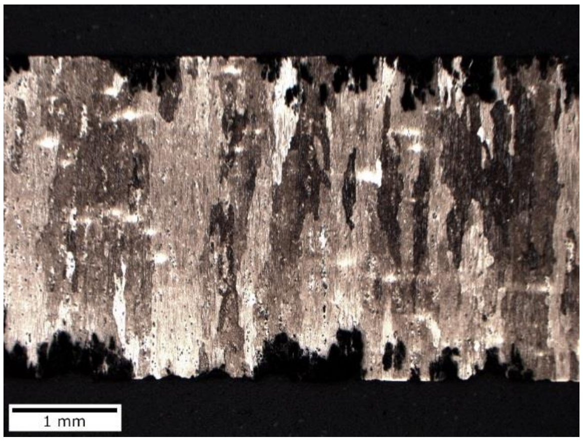
(b) 50% YS



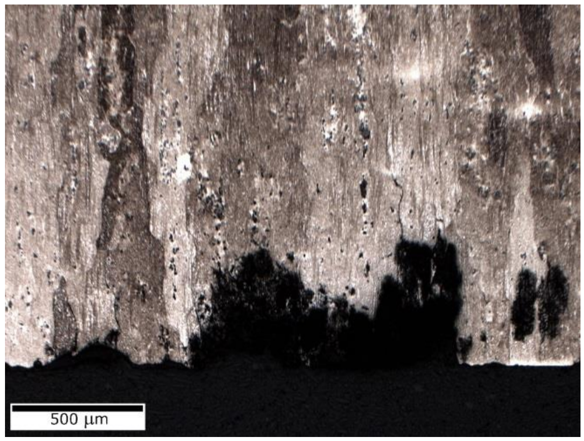
cp-p9_unetched_m01_20x.jpg



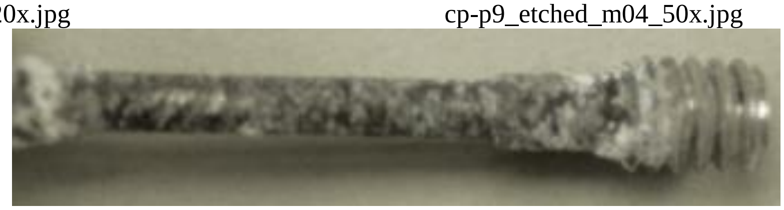
cp-p9_unetched_m02_50x.jpg



cp-p9_etched_m03_20x.jpg



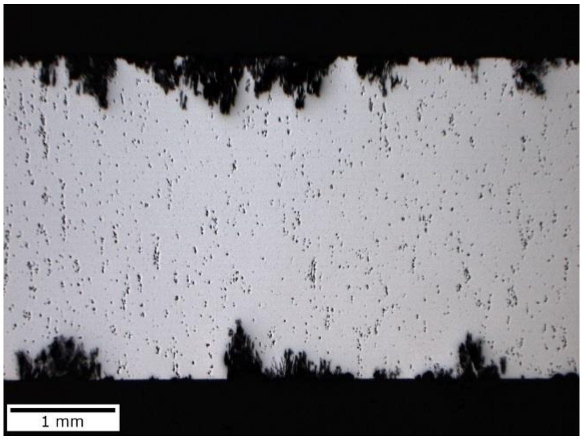
cp-p9_etched_m04_50x.jpg



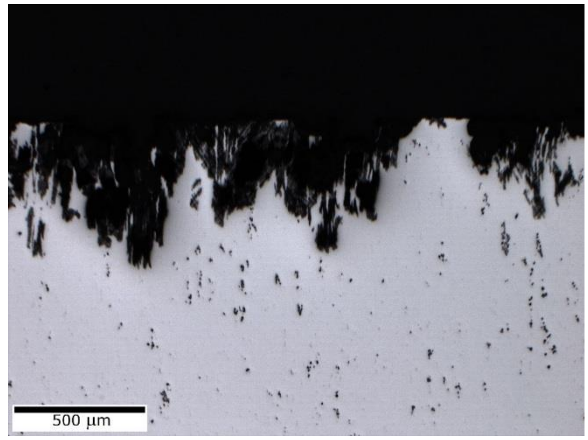
Coupon blank:	CPST dome; pole region
Specimen No.:	CP-P9
Orientation:	ST
Applied stress (% YS):	75, based on MMPDS LT YS
Applied stress (ksi):	27
Failed?:	No
SCC?:	Yes; circled in red

(c) 75% YS

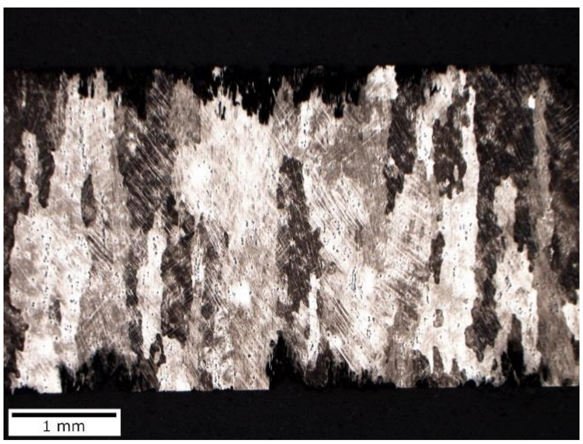
Figure 11. ***Photomicrographs of SCC specimens from the CPST dome pole following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; and (c) 75% YS.***



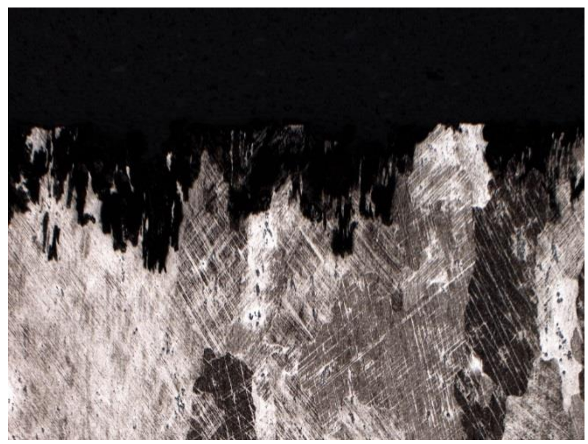
cp-r1_unetched_m01_20x.jpg



cp-r1_unetched_m02_50x.jpg

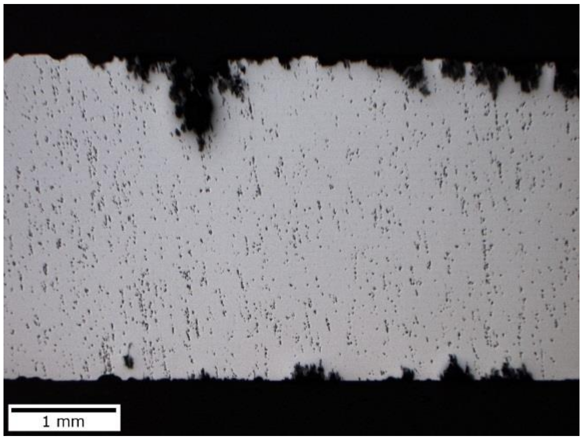


cp-r1_etched_m03_20x.jpg

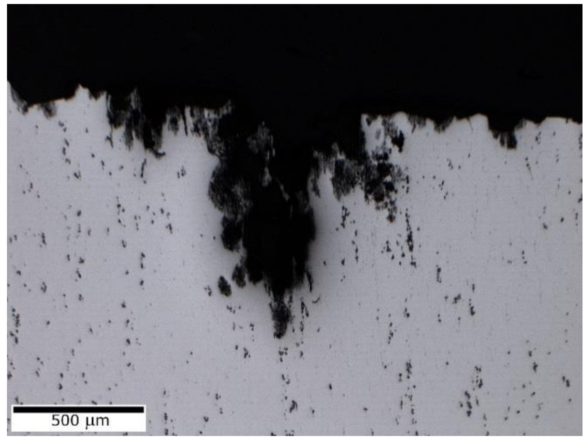

cp-r1_etched_m04_50x.jpg

Coupon blank:	CPST dome; rim region
Specimen No.:	CP-R1
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

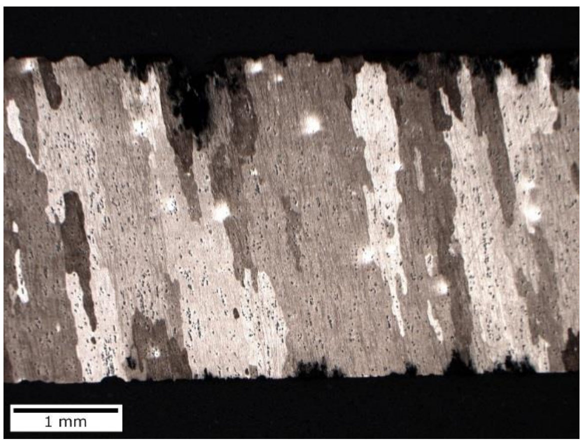
(a) 0% YS



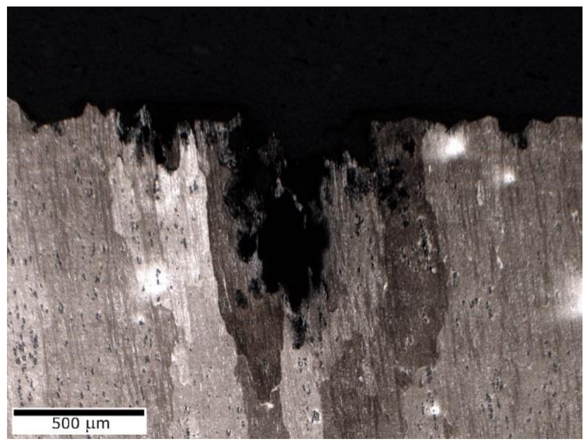
cp-r4_unetched_m01_20x.jpg



cp-r4_unetched_m02_50x.jpg



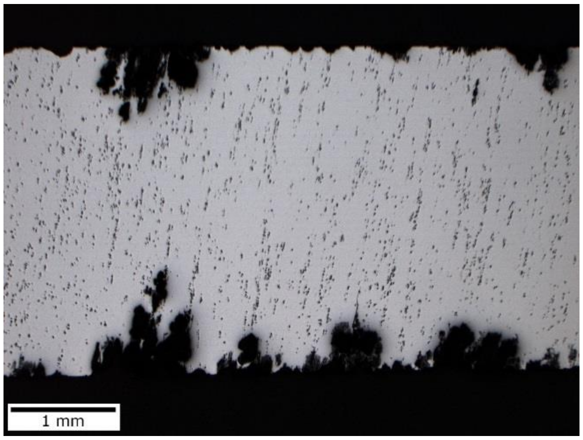
cp-r4_etched_m03_20x.jpg



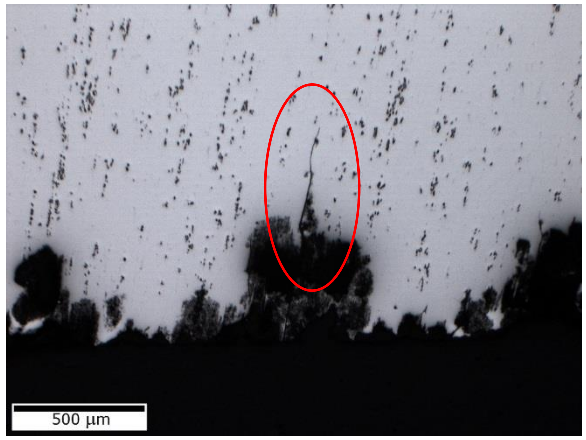
cp-r4_etched_m04_50x.jpg

Coupon blank:	CPST dome; rim region
Specimen No.:	CP-R4
Orientation:	ST
Applied stress (% YS):	50, based on MMPDS LT YS
Applied stress (ksi):	18
Failed?:	No
SCC?:	No

(b) 50% YS



cp-r7_unetched_m01_20x.jpg



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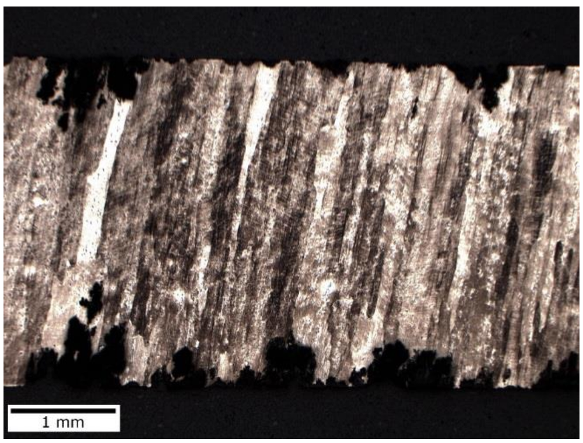

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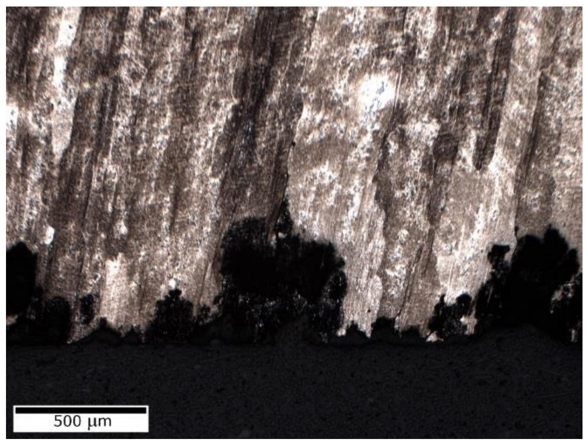


cp-r7_etched_m04_50x.jpg

Coupon blank:	CPST dome; rim region
Specimen No.:	CP-R7
Orientation:	ST
Applied stress (% YS):	75, based on MMPDS LT YS
Applied stress (ksi):	27
Failed?:	No
SCC?:	Yes; circled in red

(c) 75% YS

Figure 12. ***Photomicrographs of SCC specimens from the CPST dome rim following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; and (c) 75% YS.***

5.4 Stress Corrosion Summary

Results for all of the materials evaluated during the Phase II and supplemental SCC testing indicate that the spin forming process and associated modified heat treat practice reduces the resistance to SCC based on comparison with handbook rankings for Al 2219-T6 wrought products. Evidence of SCC was observed in material from the aft bulkhead, CPST dome, and modified plate, based on the criteria of failure during exposure, residual strength reduction, or occurrence of SCC. These materials all received the modified heat treatment, indicating that the reduced SCC resistance was likely due to the modified heat treatment and not the spin forming process. SCC failures occurred in all three products for material exposed at the minimum exposure stress level used in this study, 50% of the MMPDS ST YS for plate, indicating that the threshold stress level for SCC may be lower.

No specimens failed during the supplemental test exposures of the aft bulkhead and post-exposure residual strength ratios were above minimum required values. A retest of coupon blank M10 showed that the single specimen failure at 50% YS exposure stress was not repeatable. Similarly, tests of adjacent coupon blank J2 showed no specimen failures. A review of test procedures and specimen preparation could not identify a cause for this discrepancy with the Phase II testing and could indicate material variability. However, post-exposure microstructural examination showed SCC in the supplemental test specimens from coupon blanks M10 and J2.

Test results for the aft bulkhead indicated increasing SCC resistance with distance from the pole. In the Phase II testing the number of specimen failures during exposure was smallest at the rim and increased at the membrane and pole locations. The only specimens in the Phase II test matrix that failed the residual strength or exhibited SCC were from the pole and membrane regions. In both the Phase II and supplemental tests the percent residual strength retained was greatest at the rim, lower in the membrane, and lowest at the pole. The only supplemental test specimens that exhibited SCC were from the pole and membrane locations. Results from the CPST dome showed less well defined trends with location; however, the lowest residual strength ratio was from the pole.

Similar pass/fail results and residual strengths were observed for the standard and modified plates. However, metallurgical analysis showed evidence of SCC in the modified plate, suggesting that the reduced quench rate associated with the modified heat treatment reduced the SCC resistance. Studies to increase the quench rate while not compromising residual stress and distortion effects are recommended.

Additional SCC testing is recommended by the Orion MPCV Program and/or other users of spin formed Al 2219-T6 products to confirm trends presented by this study, to establish a threshold stress level for SCC, and to determine a maximum allowable service stress. Additional testing should be performed on multiple articles from initial serial production and should sample multiple material lots. In addition, exposure stress levels during additional testing should be successively reduced until no evidence of SCC occurs. Results from this study and any additional programmatic testing may be used to develop a Materials Usage Agreement (MUA).

The following findings, observations, and NESC recommendations are provided in response to the questions posed in Table 1 for the supplemental stress corrosion tests.

F-1. A retest of coupon blank M10 showed that the single specimen failure at 50% YS exposure stress was not repeatable.

- Material from coupon blank M10 and the adjacent blank, J2, passed the 30-day 3.5% NaCl alternate immersion exposure at 50%YS exposure stress and had acceptable residual strength ratios.
- Post-exposure microstructural examination showed SCC in both the Phase II tests of coupon blank M10 and the supplemental tests of coupon blank M10 and J2.

F-2. Aft bulkhead material from coupon blank M10 passed the 30-day 3.5% NaCl alternate immersion exposure at exposure stress levels based on MMPDS for plate and measured ST YS values for the aft bulkhead.

F-3. Material from additional locations in the aft bulkhead passed the 30-day 3.5% NaCl alternate immersion exposure at exposure stress levels based on MMPDS YS values for plate and exhibited residual strengths above minimum required values.

- Residual strength values were higher at the rim as compared with the pole and membrane locations.

F-4. The combined spin forming process and associated modified heat treat practice reduces the SCC resistance compared with wrought plate, likely related to the slower quench rate associated with the modified heat treatment.

- While no SCC failures occurred during 30-day alternate immersion exposure in a 3.5% NaCl environment, post-exposure metallurgical evaluation showed SCC in the spin formed aft bulkhead and CPST dome materials subjected to the modified heat treatment.
- Remnant plate processed using the modified heat treatment exhibited lower post-exposure residual strength values than standard plate.
- Post-exposure metallurgical evaluation showed SCC in the modified plate. No evidence of SCC was found in the standard plate.

F-5. The SCC resistance of the Al 2219-T62 spin formed aft bulkhead and CPST dome were similar, indicating that the SCC behavior observed is likely representative of similarly processed Al 2219-T62 spin formed products.

O-1. The SCC data for the aft bulkhead provides insight about the SCC resistance of the spin formed Al 2219-T62 material, but is insufficient to establish a SCC threshold stress level.

- Testing in this study sampled one spin formed aft bulkhead and one material lot. Establishing a threshold requires testing of multiple serial production aft bulkheads and multiple material lots.

- Evidence of SCC was observed for all non-zero exposure stress levels indicating that the SCC threshold is below the minimum stress level used in this study.

O-2. Grain size in the CPST dome was larger than in the aft bulkhead, which may have contributed to a greater extent of pitting and lower percent tensile strength retained and residual strength ratios.

R-1. Perform additional SCC testing on spin formed Al 2219-T6 products to establish a threshold stress level for SCC and to determine a maximum allowable service stress. (O-1)

- Additional testing should be performed on multiple articles from initial serial production and should sample multiple material lots.
- Exposure stress levels should be successively reduced until there is no evidence of stress corrosion.

R-2. Perform heat treatment studies to determine whether a faster quench rate can be achieved that improves SCC resistance without compromising residual stress and distortion control. (F-4)

6.0 Supplemental Tensile Tests

6.1 Background

Based on the results of the tensile tests performed on the aft bulkhead and the limited amount of handbook data available for interpretation of the results, a limited quantity of additional tensile tests were conducted to address key questions. Table 10 shows the supplemental tensile test matrix and questions being addressed.

Table 10. Supplemental tensile test matrix and questions being addressed.

Material Source	Location / Heat Treatment	Orient.	Through-thickness position	# of Specimens	Question Addressed
Aft Bulkhead	L2	L	t/8	3	1. What are the tensile properties at other through-thickness locations in the aft bulkhead? 2. What effect does the inhomogeneous microstructure have on the tensile properties of the aft bulkhead?
			7t/8	3	
		LT	t/8	3	
			7t/8	3	
Plate	Standard (1)	L	t/2	3	3. How do the tensile properties of the aft bulkhead compare to wrought plate? 4. What effect does a slower quench during heat treat processing have on the tensile properties of the material? 5. Are the high ST tensile properties in the aft bulkhead inherent to the plate lot or are they an artifact of spin form processing?
		LT	t/2	3	
		ST	t/2	3	
Plate	Modified (2)	L	t/2	3	
		LT	t/2	3	
		ST	t/2	3	

(1) Standard: Solution heat treat @ 995°F ± 10°F / 3 hours; water quench, and age @ 375°F ± 10°F / 36 hours.
(2) Modified: Solution heat treat @ 995°F ± 10°F / 3 hours; glycol quench, and age @ 375°F ± 10°F / 36 hours.

6.2 Microstructural Analysis

Based on microstructural characterization of the aft bulkhead performed during the Phase II study, the post-recrystallization grain morphology varies with meridian distance and through-thickness position, with larger grain sizes associated with likely regions of higher deformation (3), (16). Grain sizes were larger toward the rim and toward the OML surface, which was in direct contact with the forming tool. Additional microstructural analysis of the aft bulkhead was performed in support or the supplemental tensile test matrix. No metallurgical analysis was performed on the standard or modified plate nor on the CPST dome.

For the initial test and evaluation of the aft bulkhead conducted during the Phase II study, tensile, fracture toughness, and SCC specimens extracted from the aft bulkhead were located at the t/2 through-thickness position. Metallurgical analysis performed during the Phase II study revealed that the microstructure in the aft bulkhead was most uniform with meridian distance (from pole

to rim) at t/2 as compared with other through-thickness positions. At t/2 the microstructure exhibited the greatest similarity in grain size, morphology, and extent of precipitation on prior deformation bands. Additional specimen testing was needed to determine whether there is any variation in tensile properties at other through-thickness positions, particularly those biased toward the OML.

The through-thickness microstructure at locations from pole to rim were examined in the Phase II characterization of the aft bulkhead using meridian arc length coupon blank L7 (Figure 13). Coupon blank L2 matched the location on L7 that exhibited the greatest through-thickness variation in microstructure so this blank was selected for the supplemental tensile tests. The location of specimens machined from coupon blank L2 are shown in Figure 14. Noted are the locations of the Phase II and supplemental test specimens. Metallurgical samples were prepared from machining remnants adjacent to the L and LT supplemental test specimens. Samples of the LT-S and L-S planes were polished through various grades of silicon carbide paper and then colloidal diamond paste. Following polishing, the samples were etched with Keller's reagent and were examined using optical microscopy to evaluate variability in grain morphology and uniformity through the thickness at each location.

The through-thickness microstructure of the machining remnants of the L and LT supplemental test specimens for coupon blank L2 is shown in Figure 15 for the L-S and LT-S planes. The grain size was smallest at the inner mold line (IML) where the material was in contact with the supporting mandrel and largest towards the OML where deformation was greatest (due to the forming tool contacting the material). The larger grain size was due to strain induced recrystallization. The t/8 and 7t/8 positions showed significant difference in grain size compared to the t/2 position and were selected for the supplemental test specimen position. In addition, the membrane region of the finished machined aft bulkhead will likely be located near the OML surface so tensile properties from this region will be of most interest to the Orion designers.

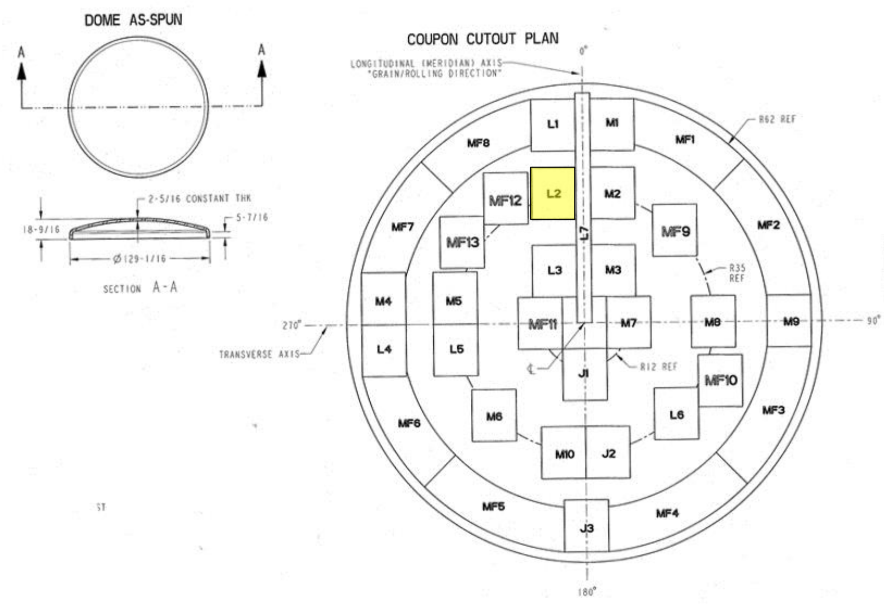


Figure 13. Aft bulkhead cut plan showing the location of the tensile coupon blank for supplemental testing highlighted in yellow.

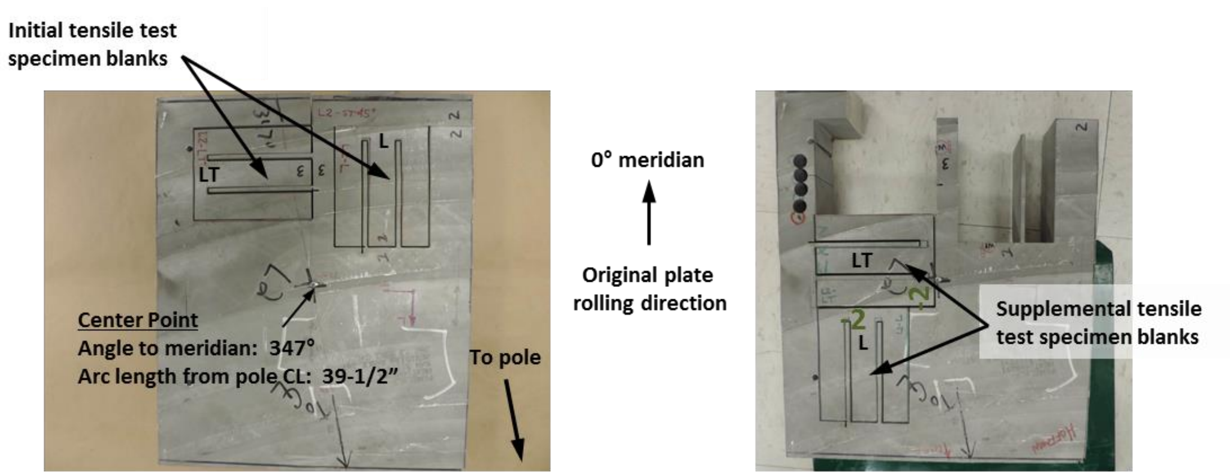
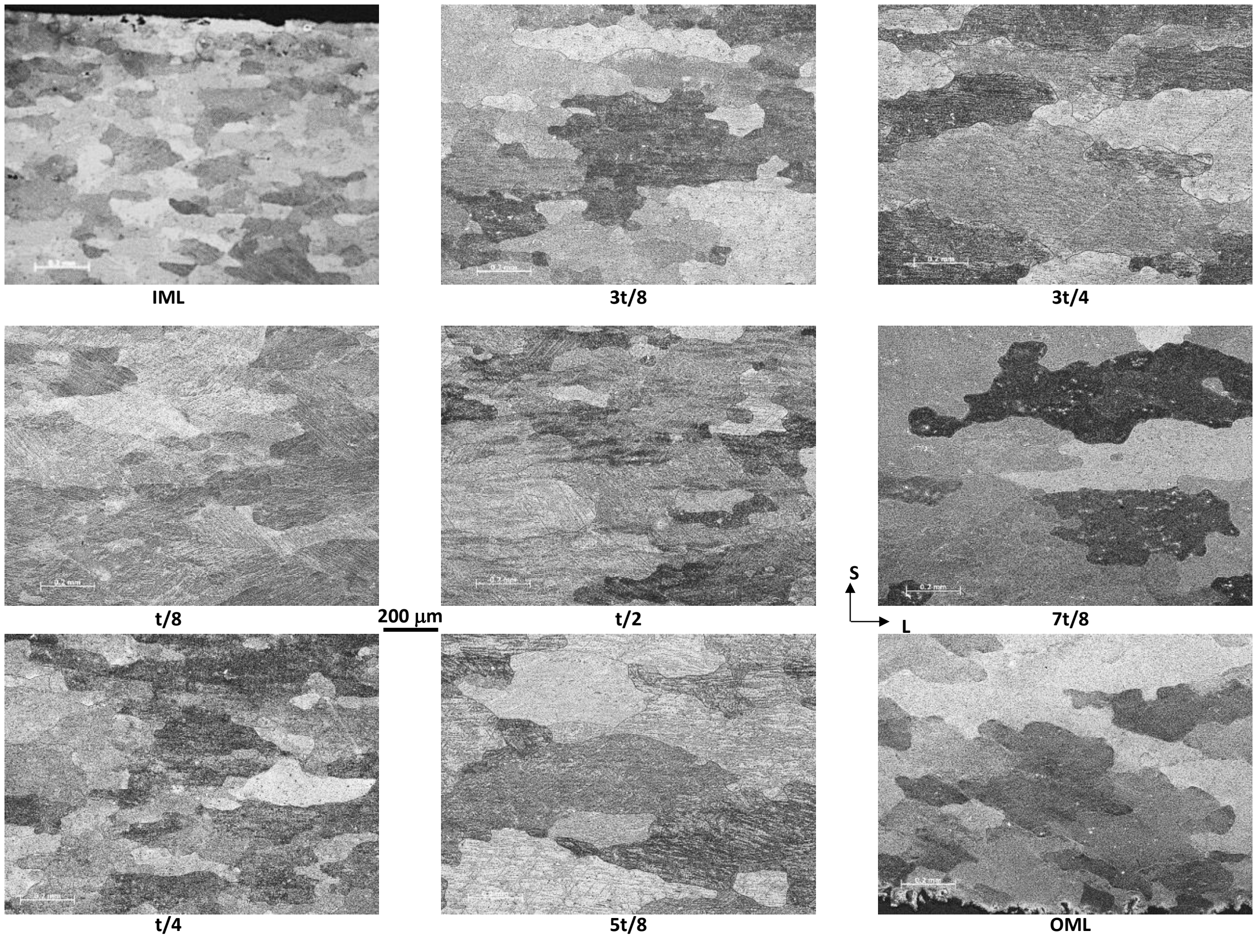
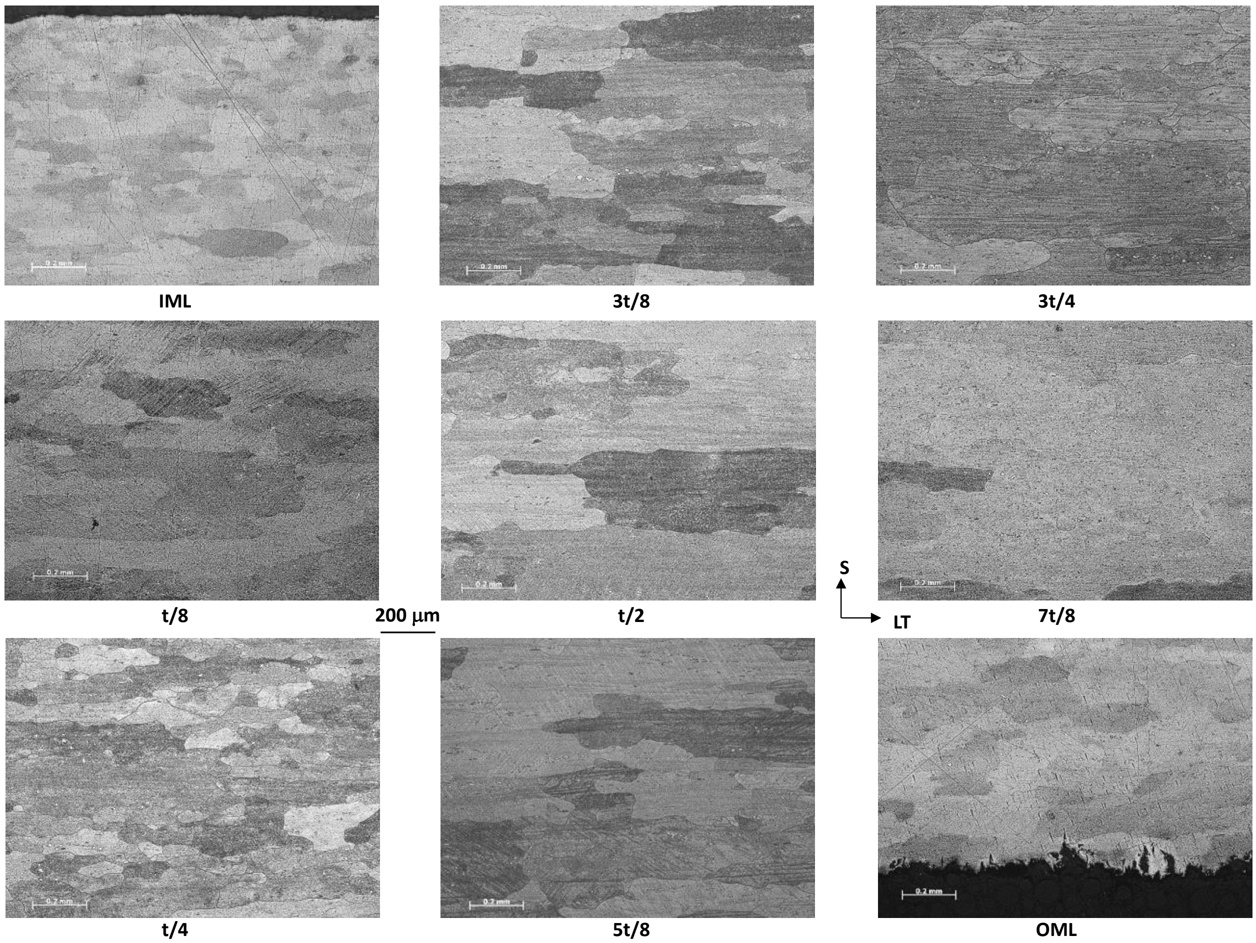


Figure 14. Coupon blank L2 showing the locations of the Phase II and supplemental tensile specimens.



(a) L-S plane



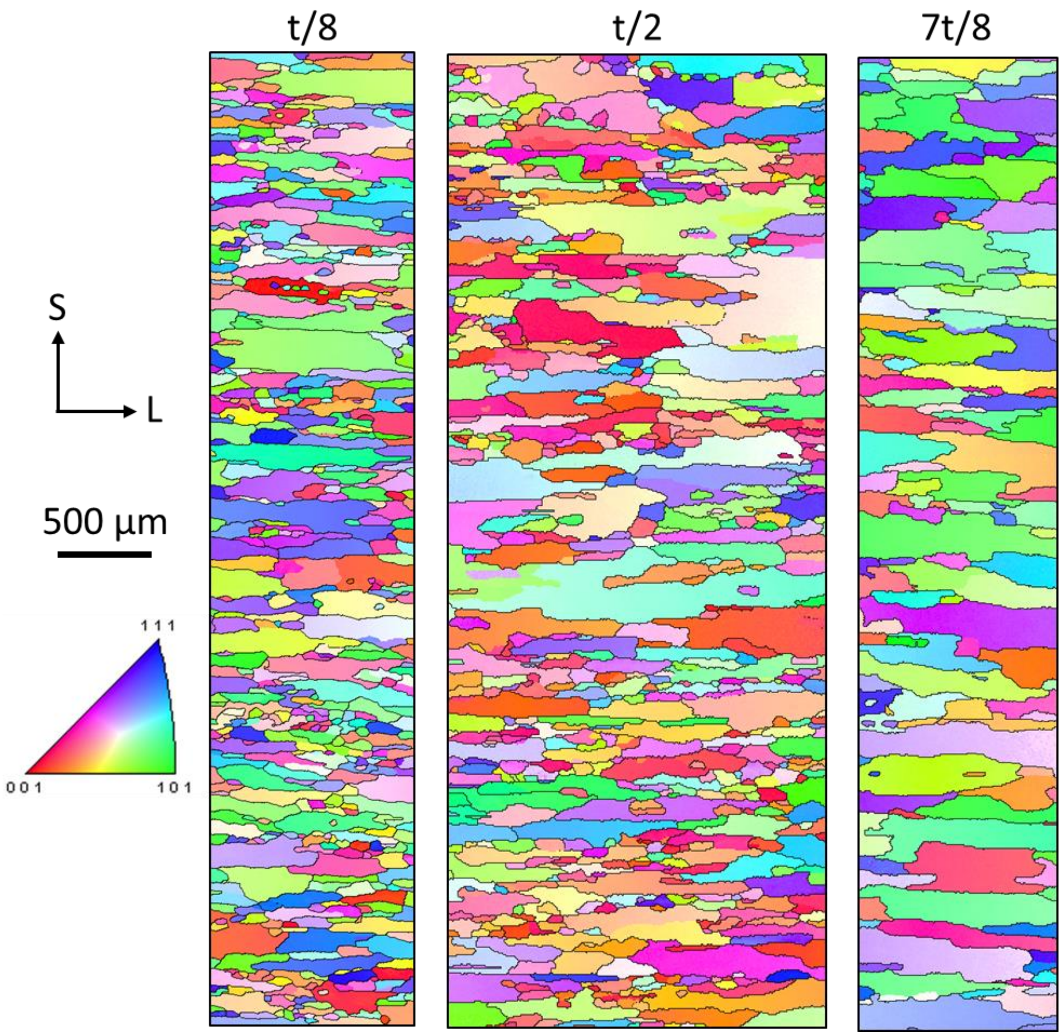
(b) LT-S plane

Figure 15. Through-thickness microstructure of aft bulkhead coupon blank L2 in the (a) L-S plane and (b) LT-S plane.

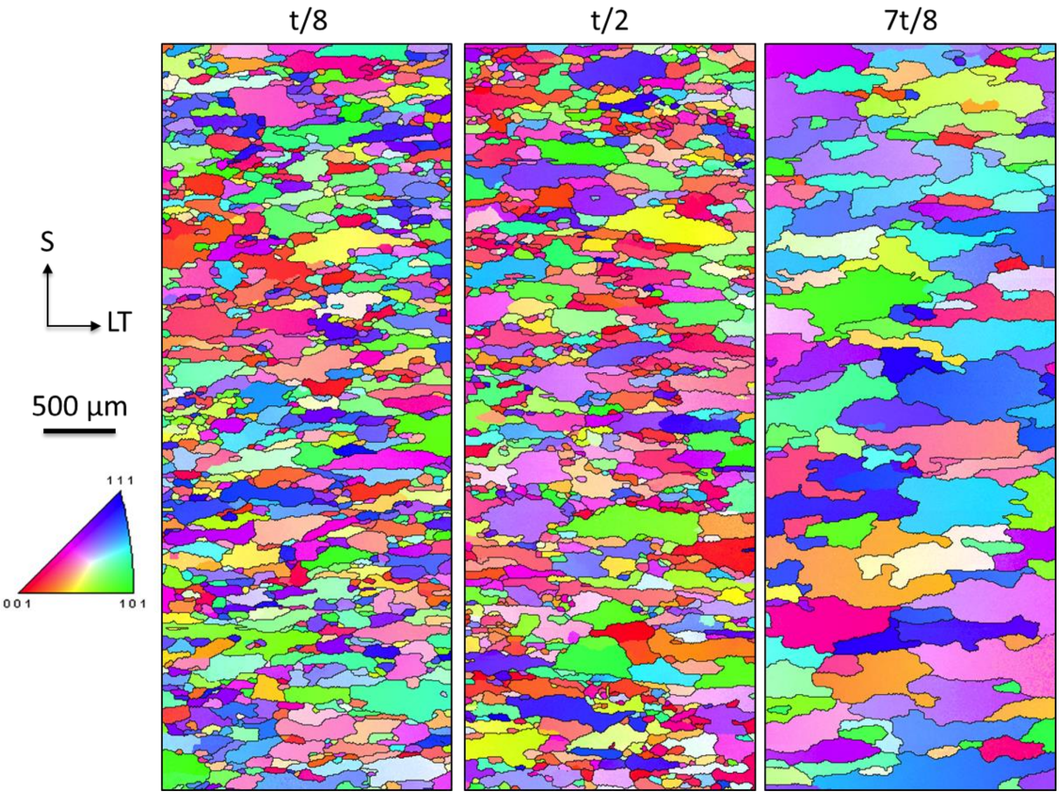
Electron backscatter diffraction (EBSD) was used to quantitatively determine grain size and texture of coupon blank L2 at the t/8, t/2, and 7t/8 through-thickness positions shown in Figure 15. Regions approximately 0.06 to 0.08 inch x 0.25 inch were scanned at each thickness position for the L-S and LT-S planes. The larger grain size at the t/8 (OML) is evident in the inverse pole figure maps shown in Figure 16. The grain size at t/8 and t/2 appear similar. Grain sizes at each location were quantified using average intercept lengths in the L / LT and ST orientations in each image, ASTM grain size number, and average grain area and the results are summarized in Table 11. The results confirm that the largest grain size occurs at 7t/8 (near the OML surface), with intercept lengths in both dimensions twice that of the t/8 and t/2 positions and grain areas three to six times larger.

Through-thickness variations in texture were evaluated from the EBSD data and are shown in Figure 17 and Figure 18 as texture maps and pole figures, respectively, for the t/8, t/2, and 7t/8

positions for the L-S and LT-S planes. In Figure 17 each color represents all variants for a given texture components within 20 degrees. The texture analysis reveals a mix of shear, compressive deformation (Brass and Copper), and cube components, with the shear and cube being most dominant. More brass and copper are observed at t/8 (near the IML), indicative of compression of material against the forming mandrel. The pole figures indicate similar texture distributions for the L-S and LT-S planes. Stronger textures were observed at t/2 and 7t/8 (near the OML) reflecting the higher degree of deformation associated with contact by the forming roller.



(a) L-S plane

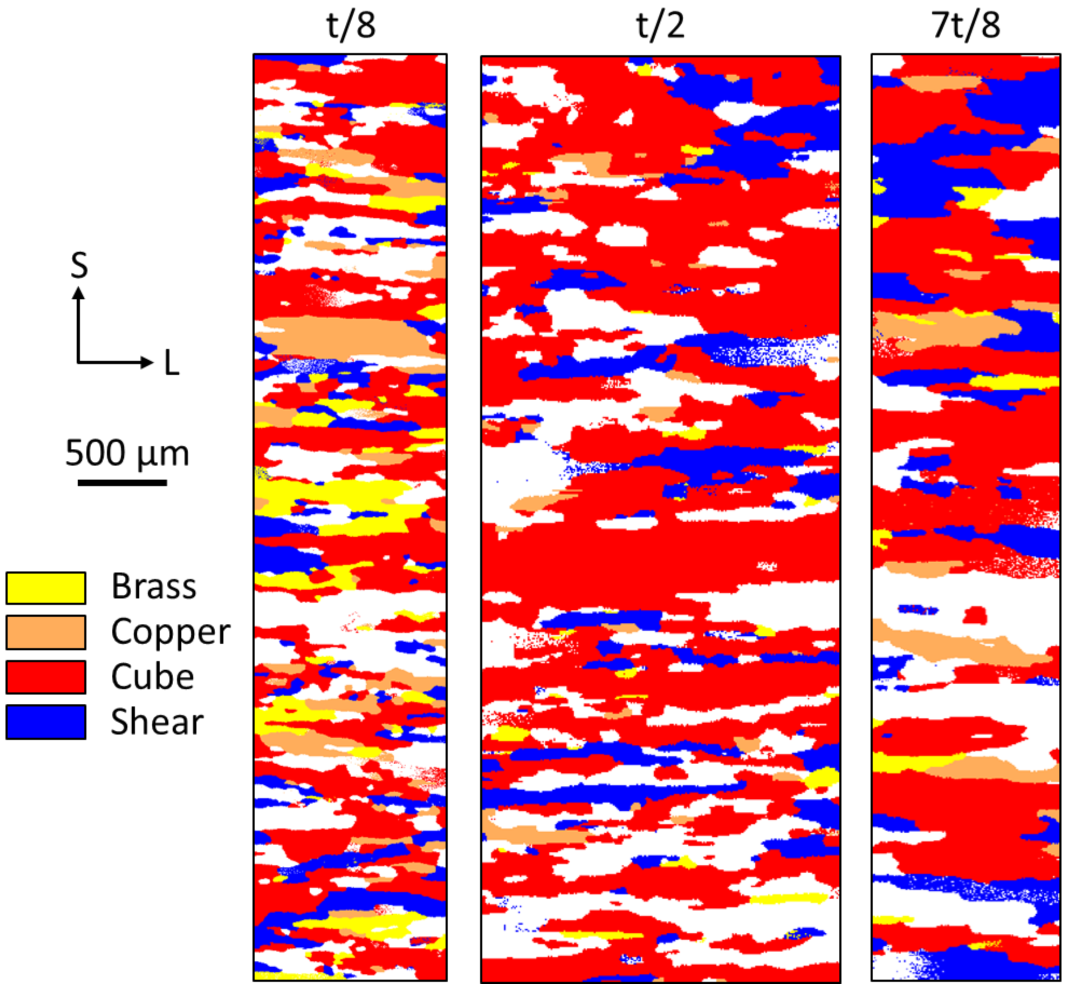


(b) LT-S plane

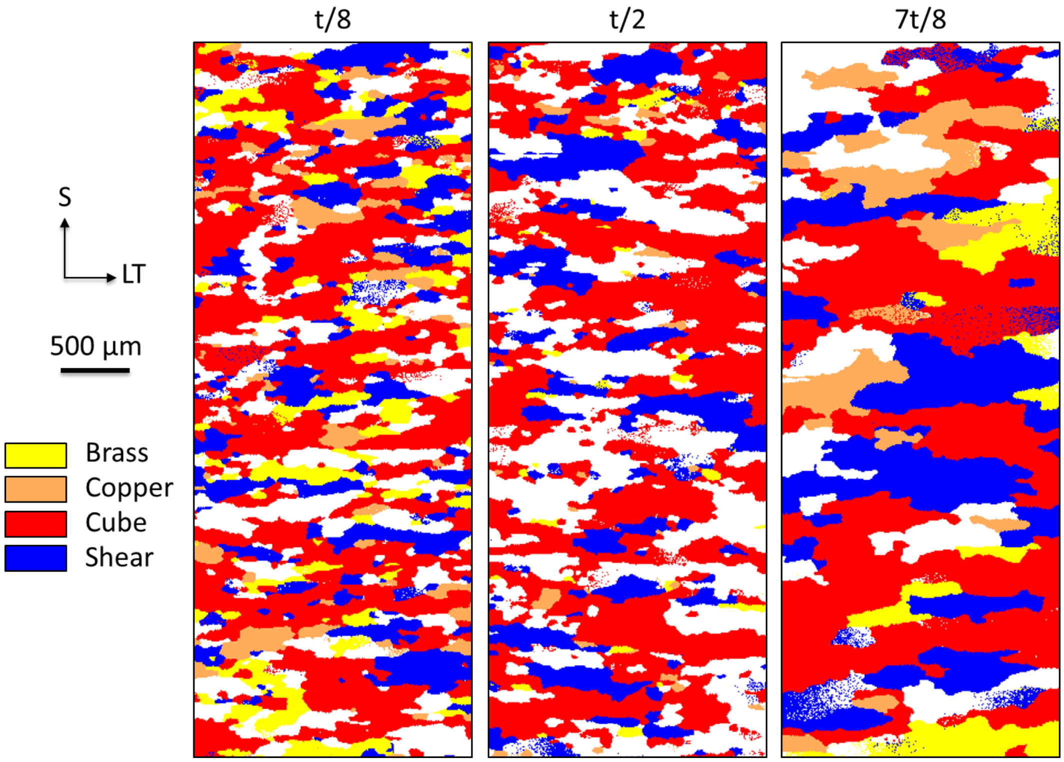
Figure 16. Inverse pole figure maps at t/8, t/2, and 7t/8 of aft bulkhead coupon blank L2 for the (a) L-S and (b) LT-S planes.

Table 11. Grain sizes for the L and LT planes at t/8, t/2, and 7t/8 of aft bulkhead coupon blank L2.

Orient.	Through-thickness position	Intercept Length µm		ASTM #	Grain Area μm^2
		ST	L or LT		
L	t/8	72.3	156	3.8	18,950
	t/2	76.7	169.4	3.8	22,031
	7t/8	130.1	274.8	2.4	68,502
LT	t/8	74.7	134.3	4	16,296
	t/2	76.9	136.2	4	16,682
	7t/8	151.7	285.7	1.6	98,270

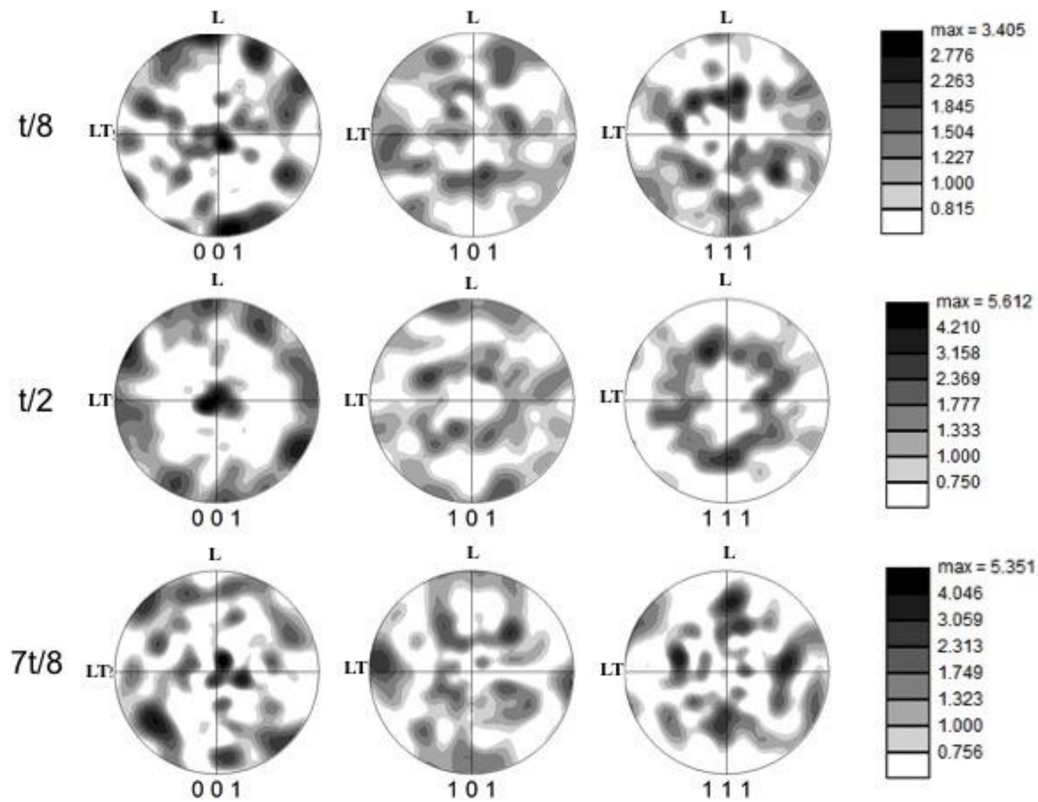


(a) L-S plane

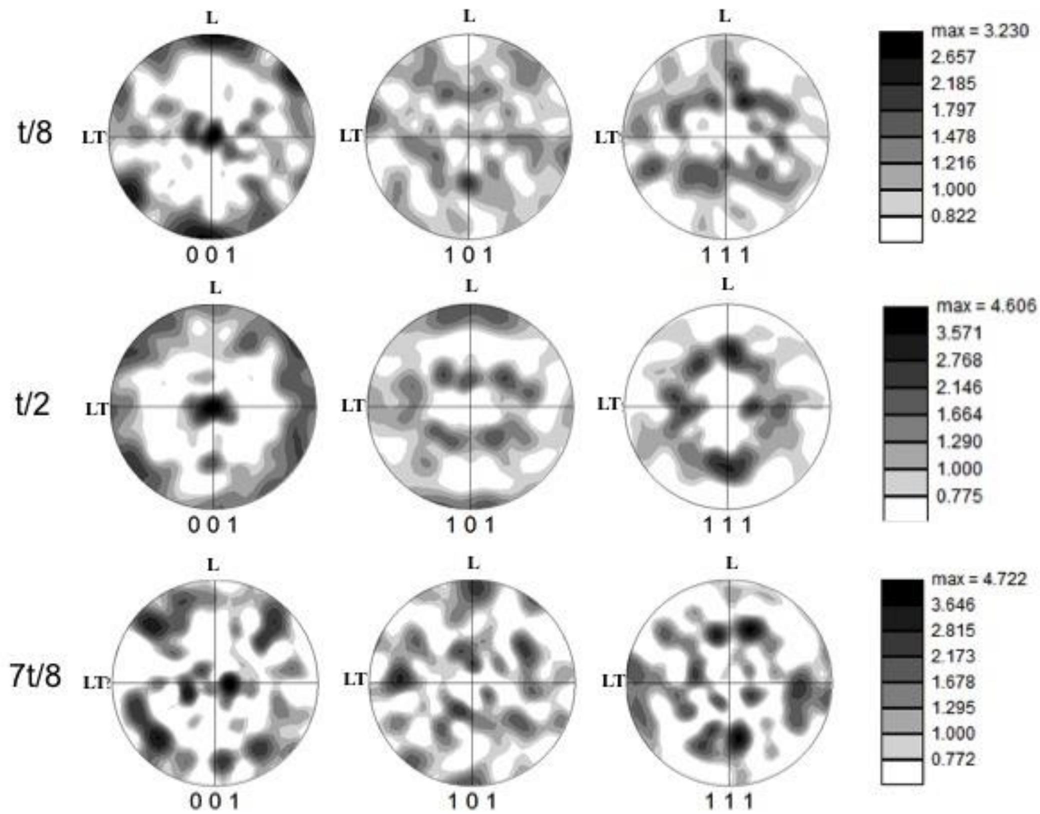


(b) LT-S plane

Figure 17. Texture maps at t/8, t/2, and 7t/8 of aft bulkhead coupon blank L2 for the (a) L-S and (b) LT-S planes.


t/8
t/2
7t/8
L
LT
0 0 1
1 0 1
1 1 1
max = 3.405
2.776
2.263
1.845
1.504
1.227
1.000
0.815
max = 5.612
4.210
3.158
2.369
1.777
1.333
1.000
0.750
max = 5.351
4.046
3.059
2.313
1.749
1.323
1.000
0.756

(a) L-S plane



(b) LT-S plane

Figure 18. ***Pole figures for the t/8, t/2, and 7t/8 through-thickness positions of aft bulkhead coupon blank L2 for the (a) L-S and (b) LT-S planes.***

6.3 Heat Treat Practice

Additional testing was designed to address the heat treat practice used in the processing of the aft bulkhead as described in Section 7.8 of Phase II Spin Formed Aft Bulkhead report (3). The solution heat treat and quench operation used by Spincraft consisted of a quench in a water/glycol mixture, which results in a slower overall cooling rate compared with a water quench to reduce part distortion and residual stress in the final product. Although this quench operation is permissible per AMS 2770, the slower cooling rate affects the precipitation kinetics during subsequent aging and may impact material properties (17).

F-temper plate machining remnants from the aft bulkhead forming blank were laboratory heat treat processed to the T62 temper as per AMS 2770 (18). This heat treatment consists of solutionizing at 995°F ± 10°F for a soak time of 3 hours, followed by a quench, and artificially ageing at 375°F ± 10°F for 36 hours. Two variants of this heat treatment were evaluated: standard heat treatment that used a water quench and modified heat treatment, which used a glycol quench (15-17% polymer solution type 1/water quench medium) similar to that used by

Spincraft in the heat treatment of the aft bulkhead. Figure 19 illustrates the difference in cooling rates between the quench media based on data collected from embedded thermocouples in the plates processed for the supplemental testing. Plate processed using the two heat treatments are referred to in this report as standard and modified plate.

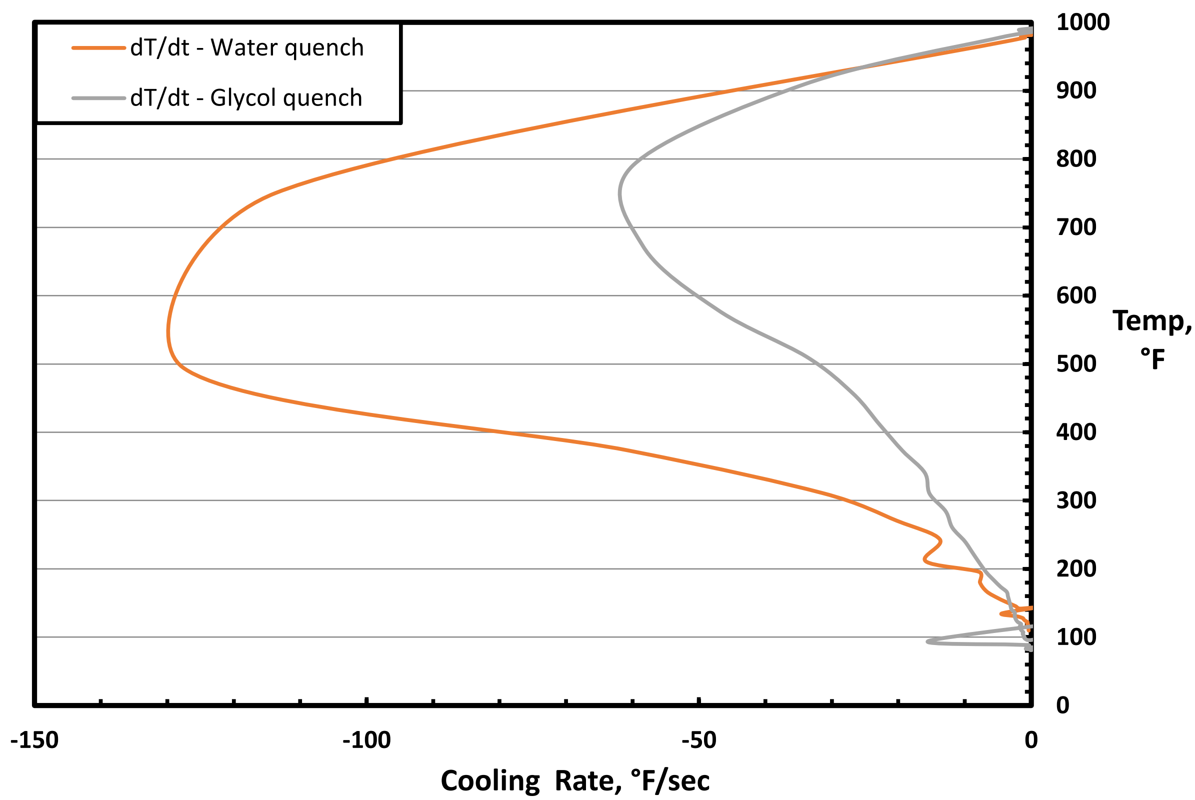


Figure 19. Cooling rate curves for water quench and glycol quench mediums.

6.4 Tensile Test Procedures

To characterize the effects of the varying through-thickness microstructure on the tensile properties, tensile specimens from coupon blank L2 (arc length = 36.0 in; meridian angle 347°) (Figure 13) were tested at the t/8 (near the IML surface) and 7/t8 (near the OML surface) through-thickness locations for comparison to Phase II tensile test results acquired at the t/2 location. To evaluate the effect of the modified heat treatment practice, tensile specimens were machined at the t/2 thickness position from the standard and modified plates for comparison with results from the aft bulkhead.

Tensile testing of the spin formed aft bulkhead and the standard and modified plate material was conducted in accordance with ASTM E8 (12). Room temperature tensile tests were conducted in the L and LT orientations for the aft bulkhead and the L, LT, and ST orientations for the plate. These grain orientations were with respect to the original plate rolling direction. No ST orientation specimens were machined for the supplemental aft bulkhead material since through-thickness locations other than t/2 were not feasible. Two specimen designs were used; one for the L and LT orientations (Figure 20) and one for the ST orientation (Figure 21). All specimens were machined from the coupon blanks such that the test section was located at either the t/8 (near the IML surface), t/2 (mid-plane), or 7t/8 (near the OML surface) through-thickness position. Three replicate tests were conducted for each grain orientation as per the test matrices shown in Table 12.

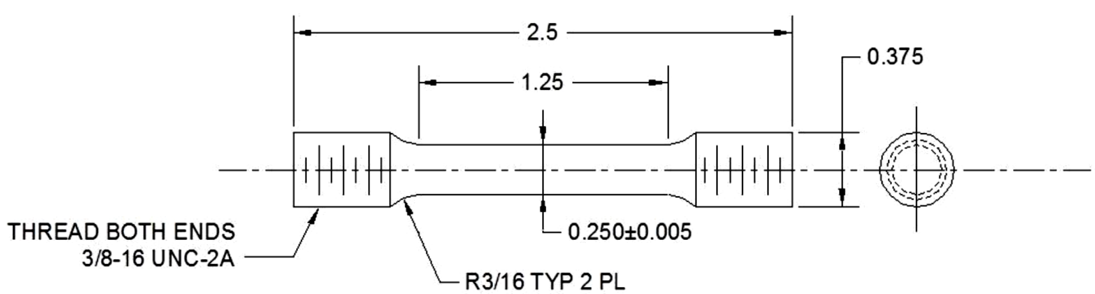


Figure 20. Round subsize tensile specimen design used for testing in the L and LT orientations (12). Dimensions are in inches.

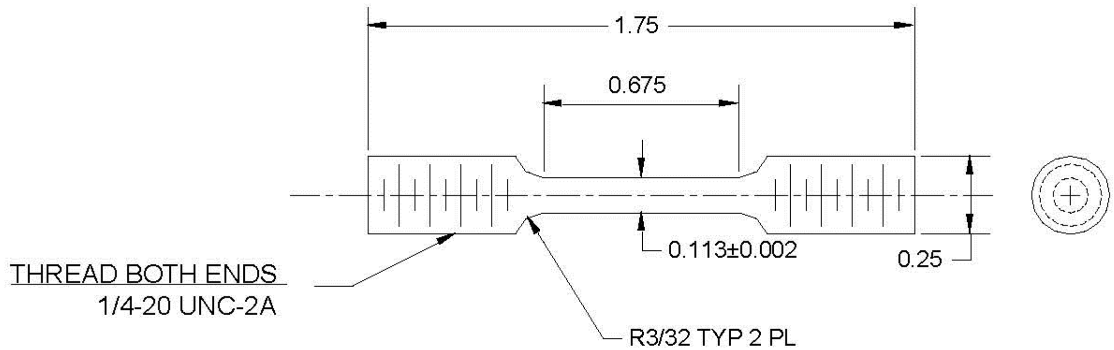


Figure 21. Round subsize tensile specimen design used for testing in the ST orientation (12). Dimensions are in inches.

Table 12. Supplemental tensile test matrix for the aft bulkhead and remnant plate material.

Product Form	Location / Heat Treatment	Orient.	Through-thickness Location	Specimen ID
Aft bulkhead	L2	L	t/8	T-L2-L-2-t/8-74
				T-L2-L-2-t/8-76
				T-L2-L-2-t/8-78
			7t/8	T-L2-L-2-7t/8-73
				T-L2-L-2-7t/8-75
				T-L2-L-2-7t/8-77
		LT	t/8	T-L2-LT-2-t/8-79
				T-L2-LT-2-t/8-81
				T-L2-LT-2-t/8-83
			7t/8	T-L2-LT-2-7t/8-80
				T-L2-LT-2-7t/8-82
				T-L2-LT-2-7t/8-84
Plate	Standard (1)	L	t/2	T-PL-WQ-L-85
				T-PL-WQ-L-86
				T-PL-WQ-L-87
		LT	t/2	T-PL-WQ-LT-88
				T-PL-WQ-LT-89
				T-PL-WQ-LT-90
		ST	t/2	T-PL-WQ-ST-91
				T-PL-WQ-ST-92
				T-PL-WQ-ST-93
	Modified (2)	L	t/2	T-PL-GLQ-L-94
				T-PL-GLQ-L-95
				T-PL-GLQ-L-96
		LT	t/2	T-PL-GLQ-LT-97
				T-PL-GLQ-LT-98
				T-PL-GLQ-LT-99
		ST	t/2	T-PL-GLQ-ST-100
				T-PL-GLQ-ST-101
				T-PL-GLQ-ST-102

(1) Standard: Solution heat treat @ 995°F ± 10°F / 3 hours; water quench, and age @ 375°F ± 10°F / 36 hours.
(2) Modified: Solution heat treat @ 995°F ± 10°F / 3 hours; glycol quench, and age @ 375°F ± 10°F / 36 hours.

Tensile tests were conducted in a servo-hydraulic test machine at a displacement rate of 0.01 in/min (ipm) to specimen failure using the test setup shown in Figure 22. Back-to-back extensometers with either a 1.000 in (L and LT specimens) or 0.500 in (ST specimens) gauge length were used to measure specimen strain response. Ultimate tensile strength (UTS), 0.2% YS, and percent elongation (e) were determined for each test condition. The modulus of elasticity (E) was calculated from the stress-strain plot and is shown in the results section as a reference value. Figure 23 shows a typical stress-strain curve for a tensile test.

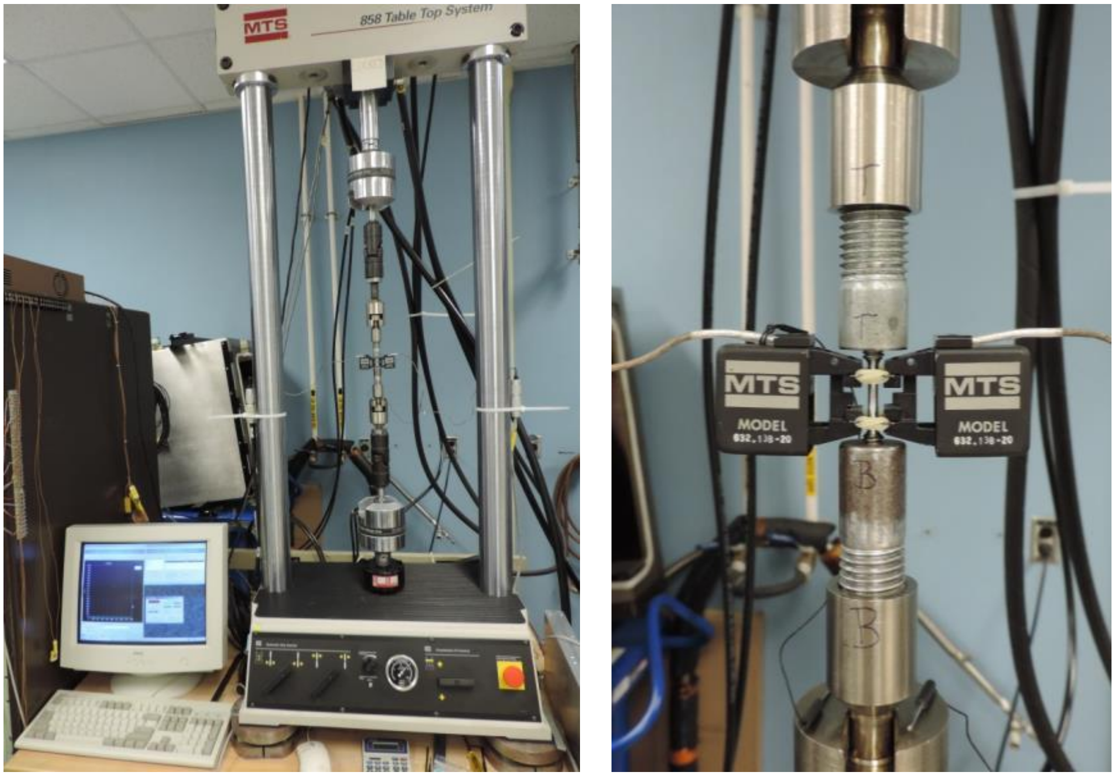


Figure 22. Tensile test load stand, specimen, and instrumentation.

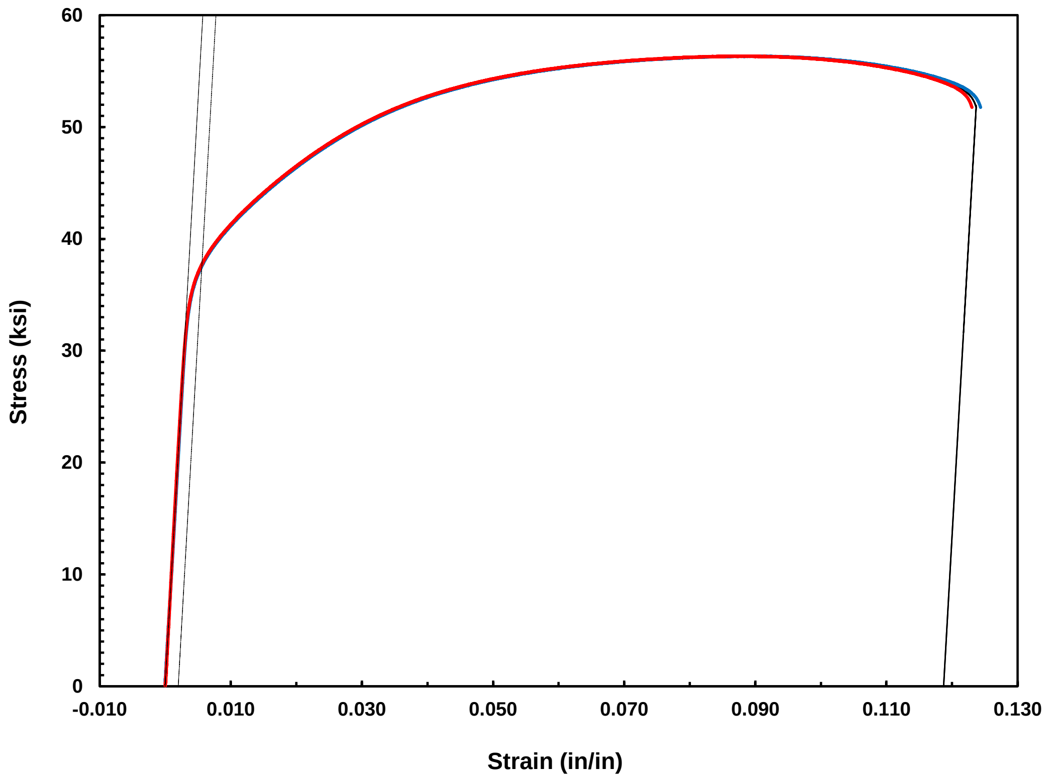


Figure 23. ***Typical stress-strain curve for the spin formed Al 2219-T62 aft bulkhead material in the L orientation; coupon blank L2, specimen T-L2-L-13.***

6.5 Tensile Test Results

6.5.1 Effect of Through-Thickness Position on Tensile Properties

The individual specimen tensile test results for the aft bulkhead coupon blank L2 at the t/8 and 7t/8 through-thickness positions are shown in Table 13 for the L and LT orientations. Also shown for comparison are the tensile properties at the t/2 position from the same coupon blank from the Phase II test program. The overall average tensile property values and standard deviations for these specimens are shown in for each orientation.

Table 13. Tensile properties of the spin formed Al 2219-T62 aft bulkhead material from coupon blank L2 at through-thickness positions t/8, t/2, and 7t/8 in longitudinal (L) and long transverse (LT) orientations.

Coupon Blank	Specimen ID	Through-Thickness Position	Orient.	UTS (ksi)	0.2% YS (ksi)	E (Msi)	e(tot) (%)
L2	T-L2-L-2-t/8-74	t/8	L	59.06	41.64	10.35	11.17
	T-L2-L-2-t/8-76			59.02	41.62	10.4	10.44
	T-L2-L-2-t/8-78			59.22	41.71	10.45	10.35
	T-L2-L-13	t/2	L	56.35	37.66	10.43	12.37
	T-L2-L-14			56.56	37.79	10.47	12.68
	T-L2-L-15			56.75	37.77	10.4	13.85
	T-L2-L-2-7t/8-73*	7t/8	L	---	---	---	---
	T-L2-L-2-7t/8-75			57.24	38.45	10.48	10.82
	T-L2-L-2-7t/8-77			57.11	38.52	10.42	10.47

L2	T-L2-LT-2-t/8-79	t/8	LT	58.82	41.05	10.43	9.75
	T-L2-LT-2-t/8-81			57.93	40.55	10.3	9.81
	T-L2-LT-2-t/8-83			58.04	40.74	10.38	8.56
	T-L2-LT-16	t/2	LT	56.33	37.49	10.38	10.73
	T-L2-LT-17			56.46	37.56	10.39	10.12
	T-L2-LT-18			56.1	37.35	10.44	10.61
	T-L2-LT-2-7t/8-80	7t/8	LT	56.6	38.18	10.46	9.01
	T-L2-LT-2-7t/8-82			56.81	38.42	10.46	9.25
	T-L2-LT-2-7t/8-84			56.16	38.36	10.44	8.75

* Data acquisition system malfunctioned; data set lost.

Table 14. Average tensile properties and standard deviation values for the spin formed Al 2219-T62 aft bulkhead material as a function of through-thickness position and orientation.

Coupon Blank	Orient.	Through-Thickness Position	UTS (ksi)	0.2% YS (ksi)	E (Msi)	e(tot) (%)	
L2	L	t/8	59.1	41.66	10.4	10.65	**Average**
			0.11	0.05	0.05	0.45	**Std. Dev.**
L2	L	t/2	56.55	37.74	10.44	12.97	
			0.2	0.07	0.03	0.78	
L2	L	7t/8	57.17	38.49	10.45	10.65	
			0.1	0.05	0.04	0.24	

Coupon Blank	Orient.	Through-Thickness Position	UTS (ksi)	0.2% YS (ksi)	E (Msi)	e(tot) (%)
L2	LT	t/8	58.26	40.78	10.37	9.37
			0.48	0.25	0.07	0.71
L2	LT	t/2	56.3	37.47	10.41	10.49
			0.18	0.11	0.03	0.32
L2	LT	7t/8	56.52	38.32	10.45	9.01
			0.33	0.13	0.01	0.25

The tensile strengths were uniform for each through-thickness position and orientation. Strength values varied by less than 1 ksi for each set of replicate specimens and standard deviations were less than 0.5. The t/8 through-thickness position exhibited higher UTS and YS values by approximately 2-3 ksi compared to the t/2 and 7t/8 positions for both the L and LT orientations. Values for the t/2 and 7t/8 positions were equivalent. Elongations exceeded 9% for all positions. The observed variation in material strength through the thickness may be related to the differences noted in grain size and texture at these positions, with higher strengths associated with finer grain size; however, the difference in strength was relatively small (<5%).

Tensile properties measured for the aft bulkhead were compared with MMPDS Handbook A-basis design allowable values for plate products (11) and with typical properties reported in the Alcoa Green Letter for 2219 (19). Tensile properties at all position/orientation combinations exceeded MMPDS values for plate products (Table 15) (11). Tensile strength at the t/8 position exceeded typical values (Table 15) in both L and LT orientations, but values at t/2 and 7t/8 were approximately 2 ksi lower than typical values. Elongations exceeded typical values for the L orientation at all through-thickness positions and for the LT orientation at t/2. Elongations for the LT orientation at t/8 and 7t/8 were within 1% of typical values. There was no clear trend of tensile properties with through-thickness position. The through-thickness tensile properties

exhibit the typical trend for aluminum alloys of increasing elongation with decreasing strength, although the difference in values is less than 2 ksi in strength and 2% in elongation.

Based on the uniformity in tensile properties and the favorable comparison with typical and MMPDS values, there was no detrimental effects of through-thickness grain size and texture variations on tensile properties.

Table 15. MMPDS design allowables and Alcoa typical tensile properties at room temperature for Al 2219-T62 plate (11), (19).

MMPDS Design Properties

Alloy: Al 2219
Specification: QQ-A-250/30
Product Form: Sheet and plate
Temper -T62
Thickness, in. 0.020 - 2.000

Basis	Orient.	UTS (ksi)	YS (ksi)	E (Msi)	e (%)
A	L	54	36	10.5	-----
	LT	54	36		d
B	L	55	37		-----
	LT	55	37		-----

d e, % (S-basis): 0.020 - 0.039 in., 6%; 0.040 - 0.249 in., 7 %; 0.250 - 1.000 in., 8%; 1.001 - 2.000 in., 7%

Alcoa Green Letter: Alcoa Aluminum Alloys 2219 and 2419

Alloy: Al 2219
Product Form: Sheet and plate
Temper -T62

	Orient.	UTS (ksi)	YS (ksi)	E (Msi)	e (%)
Typicals	LT	58	40	10.5	12

6.5.2 Effect of Heat Treat Variant on Tensile Properties

The individual specimen tensile test results for the Al 2219-T62 plate heat treated using the standard and modified heat treatments are shown in Table 16 for the L, LT, and ST orientations. The average tensile property values and standard deviations for each set of specimens are shown in Table 17. Also shown in Table 18 for comparison are the overall average tensile properties for all coupon blanks tested from the Phase II testing of the spin formed aft bulkhead, which was processed using the modified heat treatment. Comparisons are made to isolate the effects of spin form deformation prior to T62 heat treatment (aft bulkhead vs. modified plate) and the effect of the quench rate (standard vs. modified plate).

Table 16. Tensile properties of Al 2219-T62 plate processed using standard (water quench) and modified (glycol quench) heat treatment as per AMS 2770 (18).

Form	Heat Treat	Specimen Number	Orient.	UTS ksi	YS ksi	E Msi	e(tot) %
Plate	Standard (1)	T-PL-WQ-L-85	L	61.17	41.83	10.49	11.25
		T-PL-WQ-L-86		61.27	42.20	10.48	9.41
		T-PL-WQ-L-87		60.63	41.70	10.37	9.24
		T-PL-WQ-LT-88	LT	57.17	40.77	10.32	9.26
		T-PL-WQ-LT-89		58.45	39.62	10.38	9.87
		T-PL-WQ-LT-90		59.80	41.07	10.36	7.76
		T-PL-WQ-ST-91	ST	56.07	41.54	10.03	4.35
		T-PL-WQ-ST-92		56.56	41.69	10.16	4.60
		T-PL-WQ-ST-93		56.76	41.41	10.23	4.88
Plate	Modified (2)	T-PL-GLQ-L-94	L	55.63	38.79	10.38	12.34
		T-PL-GLQ-L-95		56.67	38.32	10.39	11.36
		T-PL-GLQ-L-96		58.56	39.27	10.36	11.80
		T-PL-GLQ-LT-97	LT	56.29	38.01	10.37	10.74
		T-PL-GLQ-LT-98		58.88	39.50	10.34	8.91
		T-PL-GLQ-LT-99		59.02	39.57	10.36	8.67
		T-PL-GLQ-ST-100	ST	55.70	42.74	10.25	4.18
		T-PL-GLQ-ST-101		55.54	42.96	10.33	4.13
		T-PL-GLQ-ST-102		54.70	42.25	10.19	3.88

(1) Standard: Solution heat treat @ 995°F ± 10°F / 3 hours; water quench, and age @ 375°F ± 10°F / 36 hours.
(2) Modified: Solution heat treat @ 995°F ± 10°F / 3 hours; glycol quench, and age @ 375°F ± 10°F / 36 hours.

Table 17. Average tensile properties and standard deviation values of Al 2219-T62 plate processed using standard and modified heat treatment as per AMS 2770 (18).

Orient.	UTS ksi		YS ksi		E Msi		e(tot) %		
	Std	Mod	Std	Mod	Std	Mod	Std	Mod	Heat Treat
L	61.03	56.95	41.91	38.79	10.45	10.38	9.97	11.83	Average
	0.34	1.49	0.26	0.47	0.07	0.01	1.11	0.49	Std. Dev.
LT	58.47	58.06	40.48	39.03	10.35	10.36	8.96	9.44	
	1.31	1.54	0.77	0.88	0.03	0.01	1.09	1.13	
ST	56.47	55.31	41.55	42.65	10.14	10.25	4.61	4.06	
	0.35	0.54	0.14	0.36	0.10	0.07	0.27	0.16	

Table 18. Average tensile properties and standard deviation values for the spin formed Al 2219-T62 aft bulkhead material.

Orient.	UTS ksi	YS ksi	E Msi	e 1.00" GL %	
L	57.1	38.2	10.5	12.14	Average
	1.64	0.86	0.59	1.23	Std Dev.
LT	56.7	37.9	10.4	10.32	
	1.67	0.90	0.42	1.02	
ST*	58.7	42.2	10.1	4.66	
	1.54	2.67	0.47	0.56	

*= 0.50” GL

The mechanical properties of age-hardenable aluminum alloys are dependent upon many factors, including the rate at which the material is cooled (quenched) after solution heat treatment. The L orientation exhibited the greatest difference in strength between the standard and modified plate with UTS and YS being 3 to 4 ksi greater for the standard plate. Conversely the LT and ST orientations exhibited similar strengths between the two heat treat conditions. The strengths of the modified plate were similar to the average values for the aft bulkhead, indicating that deformation associated with the spin forming process had no detrimental effect on tensile properties. This result indicates that the laboratory processed modified plate achieved similar quench rates to the full-scale commercially processed aft bulkhead. The YS variations in the modified plate were equivalent to those measured in the aft bulkhead, with ST YS being higher than L and LT, indicating that the higher ST YS is inherent in the plate and not the result of the spin forming process. The standard plate exhibited isotropic YS, with values for all orientations within 1 ksi. Both heat treat conditions resulted in tensile properties, which exceeded MMPDS A-basis design allowables for plate products. The L and LT YS and UTS of the standard plate exceeded typical values for plate. Values for the modified plate values were lower by less than

1 ksi. These results indicate that the modified heat treatment used by Spincraft for the aft bulkhead had no adverse effects on tensile properties.

6.6 Tensile Summary

Supplemental tensile test results confirmed that neither the grain size variations nor the quench rate adversely impacted tensile properties. Tensile strengths were uniform through the aft bulkhead thickness, with UTS and YS values within 1-2 ksi for all through-thickness positions (t/8 (IML), t/2, 7t/8 (OML) evaluated, and were comparable to the standard and modified plates. Tensile strengths were within 4 ksi for each orientation for the standard and modified plates. The YS in the standard plate was similar for all orientations. The YS in the ST orientation was higher than that for the L and LT orientations in both the aft bulkhead and modified plate indicating that this trend with orientation is inherent to this plate and not the result of the spin forming process.

The grain size in the aft bulkhead varied with distance from the pole and through the thickness of the plate, with larger grain sizes observed in regions of greater deformation, typically biased toward the OML and rim. Grain size was largest near the OML (7t/8), by a factor of three compared to the IML and t/2 positions based on grain area, likely associated with the combined stresses necessary to form the material over the mandrel. Through-thickness variations in material texture were observed, reflecting higher compression at the IML due to contact with the forming mandrel and greater overall deformation toward the OML. The variation in grain size stems from the complex and non-uniform deformation induced during spin forming as the plate is formed over the mandrel. The observed variations in grain size and texture did not adversely affect material properties.

The following findings and observation are provided in response to the questions posed in Table 10 for the supplemental tensile tests:

F-6. Tensile properties of the aft bulkhead were uniform with through-thickness position and orientation and were not adversely affected by the inhomogeneous microstructure

- Tensile strengths varied less than 5% with through-thickness position and specimen orientation, with strengths higher by 2-3 ksi at the t/8 position.

F-7. Tensile properties of the aft bulkhead were equivalent to the standard and modified plates indicating that there was no adverse effect of the slower quench rate used during processing.

F-8. Tensile properties in the ST orientation were higher than that for the L and LT orientations in both the aft bulkhead and modified plate indicating that this trend is inherent to the plate used in fabrication of the aft bulkhead and not a result of the spin forming process.

O-3. The higher tensile properties noted at the t/8 through-thickness position compared to the t/2 and 7t/8 positions may be related to the smaller grain size observed at that location.

7.0 Supplemental Fracture Toughness Tests

Based on the results of the fracture toughness tests performed on the aft bulkhead (3) and the limited fracture toughness data available in the literature for comparison and interpretation of the results, supplemental fracture toughness tests were performed as per the test matrix shown in Table 19. Also shown in the table are the questions being addressed by these supplemental tests. To isolate the effects of spin forming deformation on fracture behavior, remnant Al 2219-F plate from the spin forming blank was heat treated to the T62 temper using two heat treat variants as described in Section 6.3. Due to the lack of fracture toughness data for spin formed products, additional fracture toughness data was collected on remnant 2.5 inch thick Al 2219-T62 spin formed dome material. This dome was produced to manufacture tanks in support of the CPST Program (2), (5). Specific questions being addressed by the supplemental fracture toughness testing include whether the spin form processing compromises the fracture toughness of the material compared to standard wrought Al 2219-T62 plate and whether the slower quench used during heat treatment of the aft bulkhead, (i.e., the modified heat treat variant) has any effect on fracture toughness compared to the standard water quench rate.

Table 19. Supplemental fracture toughness test matrix and questions being addressed

Material Source	Location/Heat Treatment	Orient.	Through-thickness position	# of Specimens	Question Addressed
Plate	Standard [1]	L-T	t/2	2	1. How do the fracture toughness properties of the aft bulkhead compare to wrought plate? 2. What is the impact of the slower quench rate used during heat treat processing have on the fracture toughness of the material?
		T-L	t/2	2	
		S-T	t/2	2	
Plate	Modified [2]	L-T	t/2	2	
		T-L	t/2	2	
		S-T	t/2	2	
CPST Dome	Pole	S-T	t/2	2	3. How do the fracture toughness properties of the aft bulkhead compare to other spin formed products?
	Rim	S-T	t/2	2	

(1) Standard: Solution heat treat @ 995°F ± 10°F / 3 hours; water quench, and age @ 375°F ± 10°F / 36 hours.
(2) Modified: Solution heat treat @ 995°F ± 10°F / 3 hours; glycol quench, and age @ 375°F ± 10°F / 36 hours.

7.1 Fracture Toughness Test Procedures

Fracture toughness testing of the wrought plate and spin formed CPST dome material was conducted in accordance with ASTM E1820 (20). Per this test method, the fracture toughness is quantified in terms of J_{IC}, which is a measure of the fracture toughness of the material at the onset of stable crack extension. Fracture toughness characterization of the plate was conducted in three grain orientations, L-T, T-L and T-S[2]. For the spin formed CPST dome, specimens were

2 For the standard and modified plate material, an error was made in the cut plan and specimen layout drawings resulting in fracture toughness specimens being machined in the T-S orientation instead of S-T orientation.

sectioned from the rim and pole regions, and fracture toughness data was collected in the S-T orientation only. The test orientation designation first identifies the loading direction and is followed by the crack growth orientation as they relate to the grain orientation of the material. Fracture toughness was measured using a compact tension (C(T)) specimen configuration. Two specimen designs were used; one for the L-T and T-L orientations (Figure 24) and one for the S-T and T-S orientations (Figure 25). All specimens were machined from the coupon blanks such that the test section was located at the mid-plane thickness (t/2) of the coupon blank. Two replicate tests were conducted for each grain orientation as per the test matrix shown in Table 19. The test apparatus used for fracture toughness testing is shown in Figure 26.

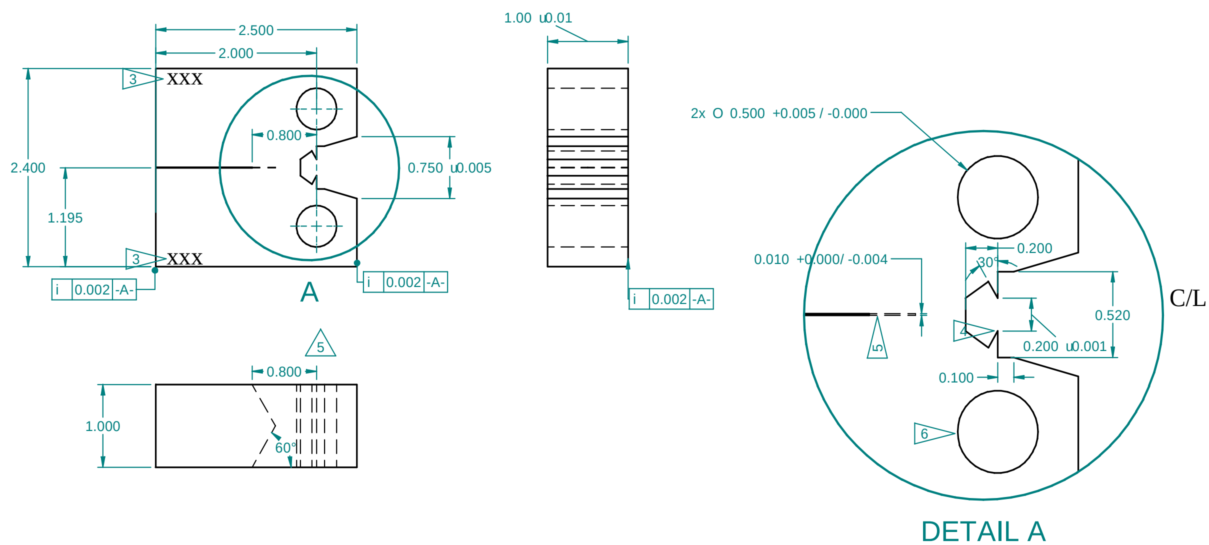


***Figure 24.** J_{IC} fracture toughness specimen design; L-T and T-L orientations. All dimensions are in inches (20).*

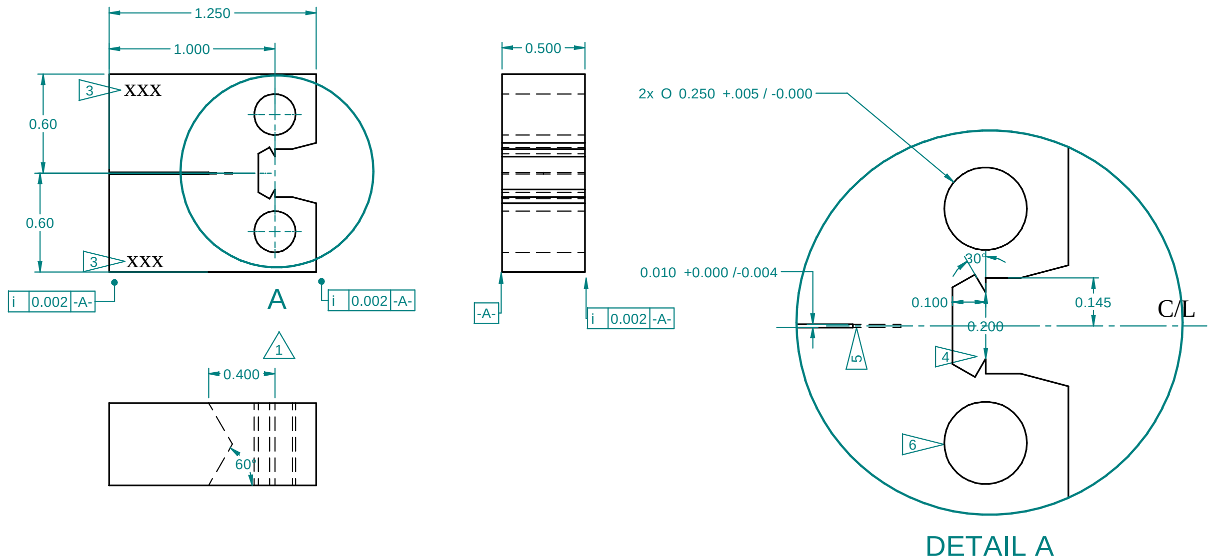


Figure 25. J_{IC} fracture toughness specimen design; S-T and T-S orientations. All dimensions are in inches (20).

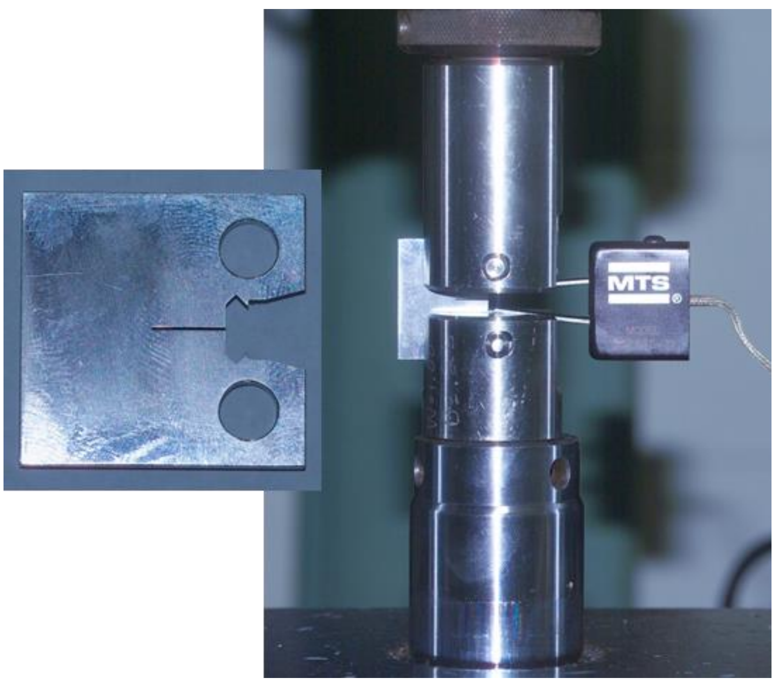


Figure 26. J_{IC} fracture toughness specimen and test apparatus.

7.2 Fracture Toughness Test Results

7.2.1 Aft Bulkhead Fracture Toughness Results

To assist in the comparison and interpretation of the supplementary fracture toughness results, the aft bulkhead data generated during the Phase II test program are presented here for reference. The aft bulkhead cut plan with the location of coupon blanks highlighted in yellow from which fracture toughness specimens were excised for fracture toughness testing is shown in Figure 27. Table 20 shows the size and location of these coupon blanks with respect to the original plate rolling direction and distance from the aft bulkhead pole to the coupon blank center point. These coupon blank locations were designed to determine uniformity of fracture toughness properties throughout the aft bulkhead and were evaluated along selected meridian and circumferential lines.

A summary of the fracture toughness test results for the spin formed Al 2219-T62 aft bulkhead material is provided in Table 21 (3). All but five specimens were valid per the ASTM E1820 specification. In each case the invalidity was related to the difference between the estimated crack extension and the measured crack extension. In each case the deviation was considered minor and inconsequential to the toughness results.

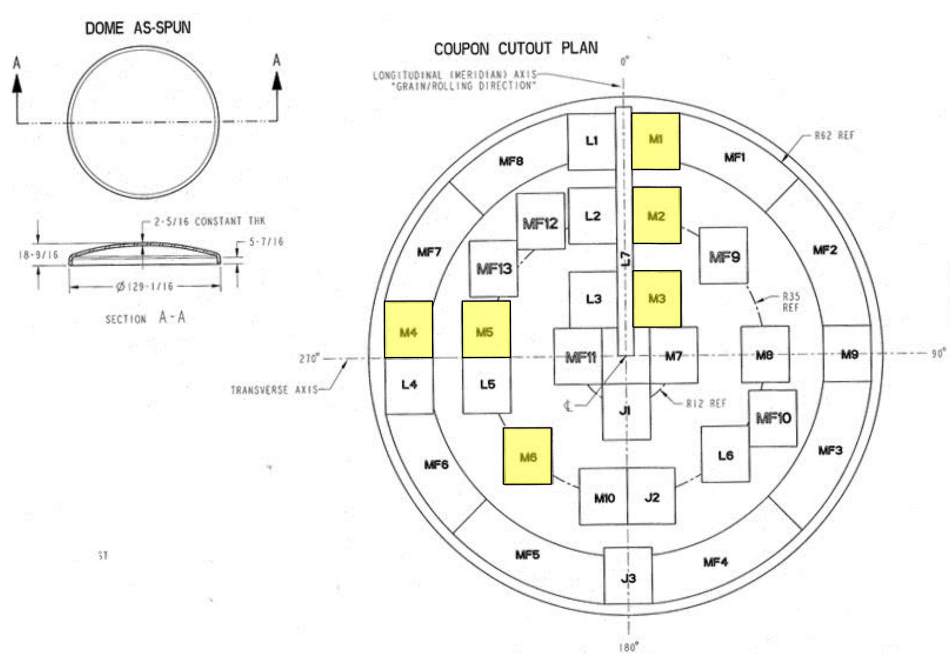


Figure 27. Aft bulkhead cut plan showing the location of the fracture toughness test coupon blanks highlighted in yellow.

Table 20. Fracture toughness coupon blank locations and orientations.

Coupon Blank	Coupon Blank Size		Coupon Center Point	
	Longitudinal Dimension, in.	Transverse Dimension, in.	Meridian Angle , degrees	Arc Length from dome CL in.
M1	14	12	9°	54-5/8
M2	14	12	13°	36
M3	14	12	30°	16-1/8
M4	14	12	277°	55-1/2
M5	14	12	281°	35-7/8
M6	14	12	225°	35-1/8

Table 21. Summary of fracture toughness data for the spin formed Al 2219-T62 aft bulkhead material (3).

Specimen ID	Coupon Blank	Orient.	J_{IC} in-lb/in^2	K_{JIC} ksi$\sqrt{}$in
CP-406-191	M1	L-T	105.6	35.1
CP-406-193			114.8	36.6
CP-406-196		T-L	91.5*	32.7
CP-406-198			90.6*	32.5
CP-406-201		S-T	62.6	27.0
CP-406-203			62.2	26.9
CP-406-206	M2	L-T	115.1	36.6
CP-406-208			112.8	36.3
CP-406-211		T-L	86.2*	31.7
CP-406-213			91.0	32.6
CP-406-216		S-T	89.9	32.4
CP-406-218			56.0	25.6
CP-406-221	M3	L-T	117.2	37.0
CP-406-223			125.7	38.3
CP-406-226		T-L	84.9	31.5
CP-406-228			93.1	32.9
CP-406-231		S-T	66.0	27.7
CP-406-233			90.7	32.5
CP-406-236	M4	L-T	102.5	34.6
CP-406-238			99.1	34.0
CP-406-241		T-L	86.0	31.7
CP-406-243			93.4*	33.0
CP-406-246		S-T	78.0	30.1
CP-406-248			50.9	24.4
CP-406-251	M5	L-T	108.4	35.5
CP-406-253			107.3	35.4
CP-406-256		T-L	86.3	31.7
CP-406-258			85.6	31.6
CP-406-261		S-T	67.8	28.1
CP-406-263			77.4	30.0
CP-406-266	M6	L-T	118.7	37.2
CP-406-268			114.0	36.4
CP-406-271		T-L	86.5	31.7
CP-406-273			85.0	31.5
CP-406-276		S-T	59.1	26.2
CP-406-278			57.4*	25.9

* Not valid J_{IC} value.

7.2.2 Supplemental Fracture Toughness Test Results

A summary of the supplemental study fracture toughness test results for the Al 2219-T62 wrought plate and spin formed CPST dome material is provided in Table 22. For the wrought plate material, all but three specimens were valid per the ASTM E1820 specification. In each case, the invalidity was related to an inaccurate estimate of the compliance-based predicted crack extension versus the specimen crack extension. The deviations were low and inconsequential to the toughness results. For the dome material, none of the specimens were valid. These invalidities were primarily related to an insufficient number of data points collected during crack extension. This made it difficult to determine definitive R-curve behavior, but the tests did generate sufficient data to estimate a K-based fracture toughness value.

Table 22. Summary of fracture toughness data for Al 2219-T62 wrought plate and spin form dome material.

Material Source	Location / Heat Treat	Specimen ID	Orient.	J_Q (in-lb/in^2)	K_{JQ} (ksi$\sqrt{in}$)	Valid J_{Ic}
Plate	Standard (1)	CP-406A-25	T-L	107.4	36.5	Yes
		CP-406A-27	T-L	98.5	35	Yes
		CP-406A-29	L-T	102.7	35.9	Yes
		CP-406A-31	L-T	113.9	37.8	Yes
		CP-406A-33	T-S	123.4	38.8	No
		CP-406A-35	T-S	144.3	42	Yes
Plate	Modified (2)	CP-406A-1	T-L	112.5	35.3	Yes
		CP-406A-3	T-L	77.4	30	Yes
		CP-406A-5	L-T	109.9	37.6	No
		CP-406A-7	L-T	112.3	36.2	Yes
		CP-406A-9	T-S	157.1	42.4	Yes
		CP-406A-11	T-S	136.5	39.5	No
CPST Dome	Pole	CP-406A-61	S-T	61.6	26.3	No
		CP-406A-62	S-T	47.7	23.1	No
CPST Dome	Rim	CP-406A-73	S-T	80	29.7	No
		CP-406A-74	S-T	100.8	33.3	No

(1) Standard: Solution heat treat @ 995°F ± 10°F / 3 hours; water quench, and age @ 375°F ± 10°F / 36 hours.
(2) Modified: Solution heat treat @ 995°F ± 10°F / 3 hours; glycol quench, and age @ 375°F ± 10°F / 36 hours.

7.2.3 Effect of Heat Treat Variant on Fracture Toughness

The supplemental study fracture toughness data listed in Table 22 for the standard and modified plates is plotted in Figure 28 as a function of heat treat variant and test orientation. Fracture toughness comparisons were based on K_{JQ} values listed in Table 22. The fracture toughness of the standard and modified plates was exemplary, with fracture toughness values, K_{JQ}, in the T-L, L-T, and T-S greater than or equal to 30 ksi√in. Fracture toughness values trended as expected with respect to orientation, increasing in toughness from the T-L to L-T to T-S orientation. For a given orientation, the fracture behavior did not vary with heat treatment. All of the standard and modified plate data exhibited rising R-curve behavior, indicative of stable tearing capability as shown in the typical R-curves presented in Figure 29 and Figure 30. This behavior is consistent with the R-curve behavior during fracture toughness testing of material from the spin formed aft bulkhead, which was heat treated using the modified heat treat variant.

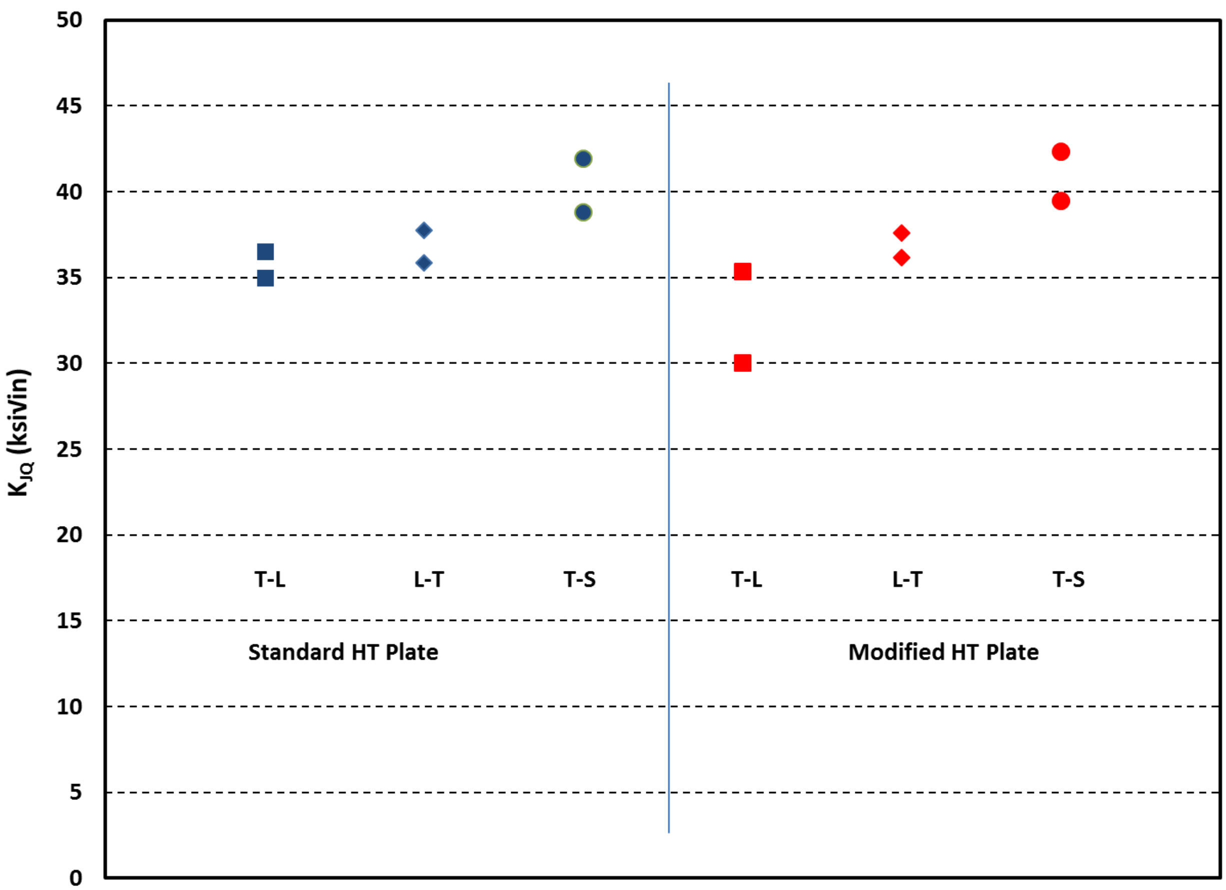


Figure 28. Fracture toughness data summary for wrought Al-2219-T62 plate heat treated using standard and modified heat treat variants.

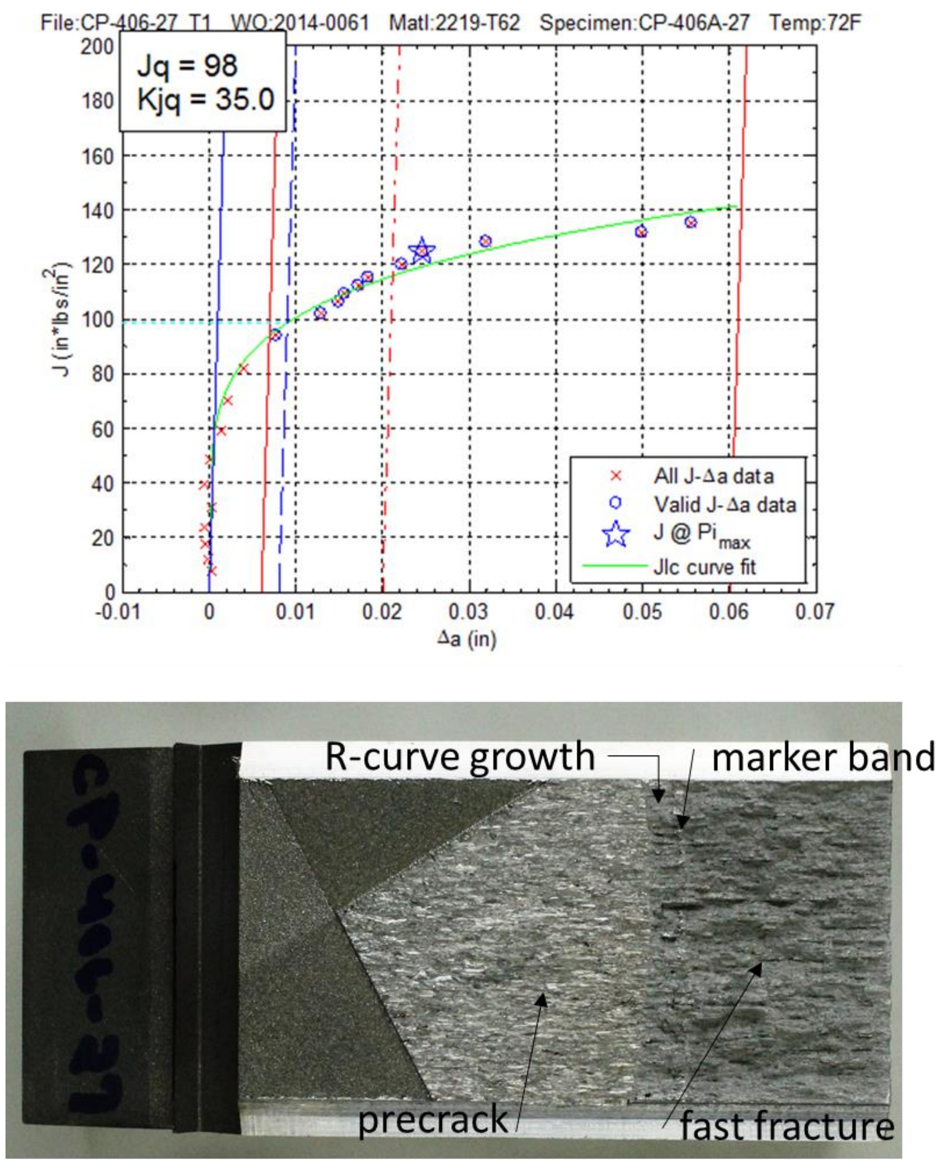
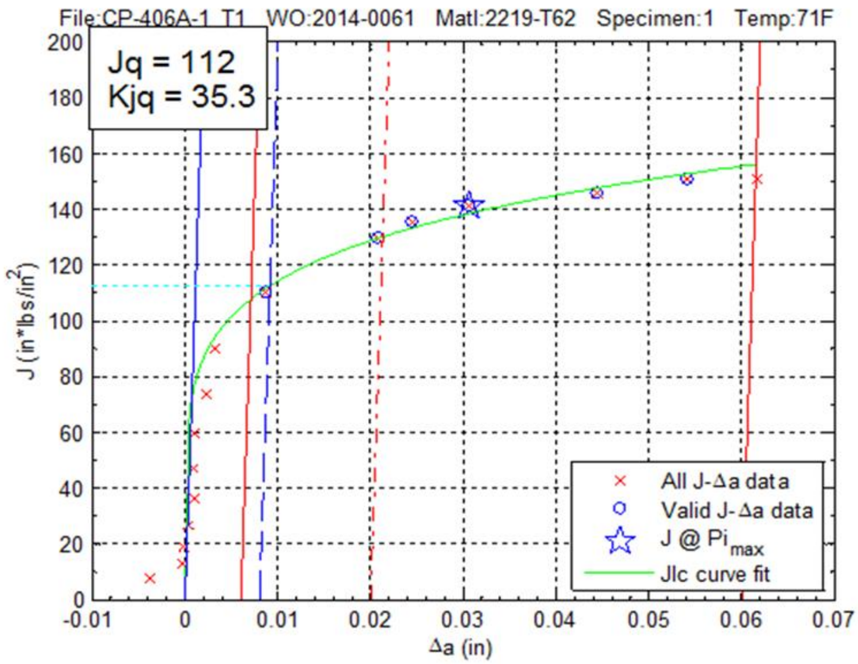


Figure 29. J-R curve and fracture surface of specimen CP-406-27 from standard heat treat Al 2219-T62 wrought plate; T-L orientation.



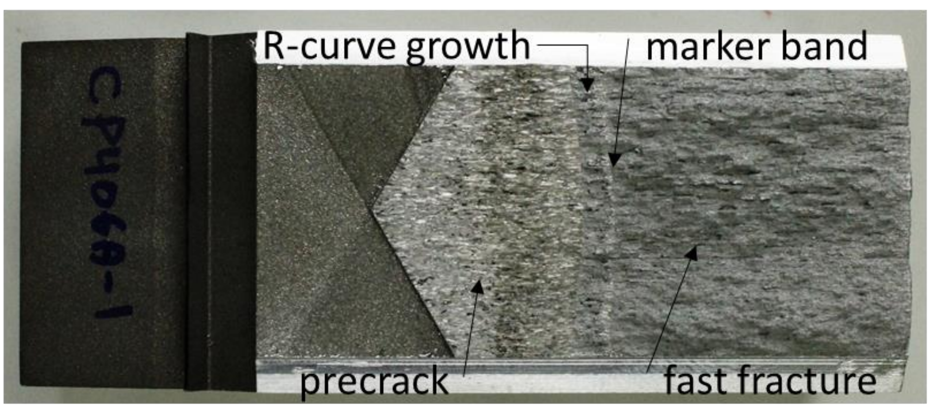


Figure 30. J-R curve and fracture surface of specimen CP-406A-1 from modified heat treat Al 2219-T62 wrought plate; T-L orientation.

Fracture toughness data in the rolling plane (T-L and L-T) from the standard and modified plates are compared to fracture toughness data from the Phase II study on the spin formed aft bulkhead (3) in Figure 31 and Figure 32. The data shown for the aft bulkhead represent all data from the various meridian and arc length locations. The L-T fracture toughness of the standard and modified plates are equivalent and the aft bulkhead was comparable to the wrought plate material. For the T-L orientation, the modified plate exhibited higher variability than was observed in the standard plate and the aft bulkhead material. The range of the modified plate and aft bulkhead data overlap and can be considered equivalent. Based on average data, the T-L

fracture toughness performance of the standard plate may be judged as better than the modified plate and spin formed aft bulkhead.

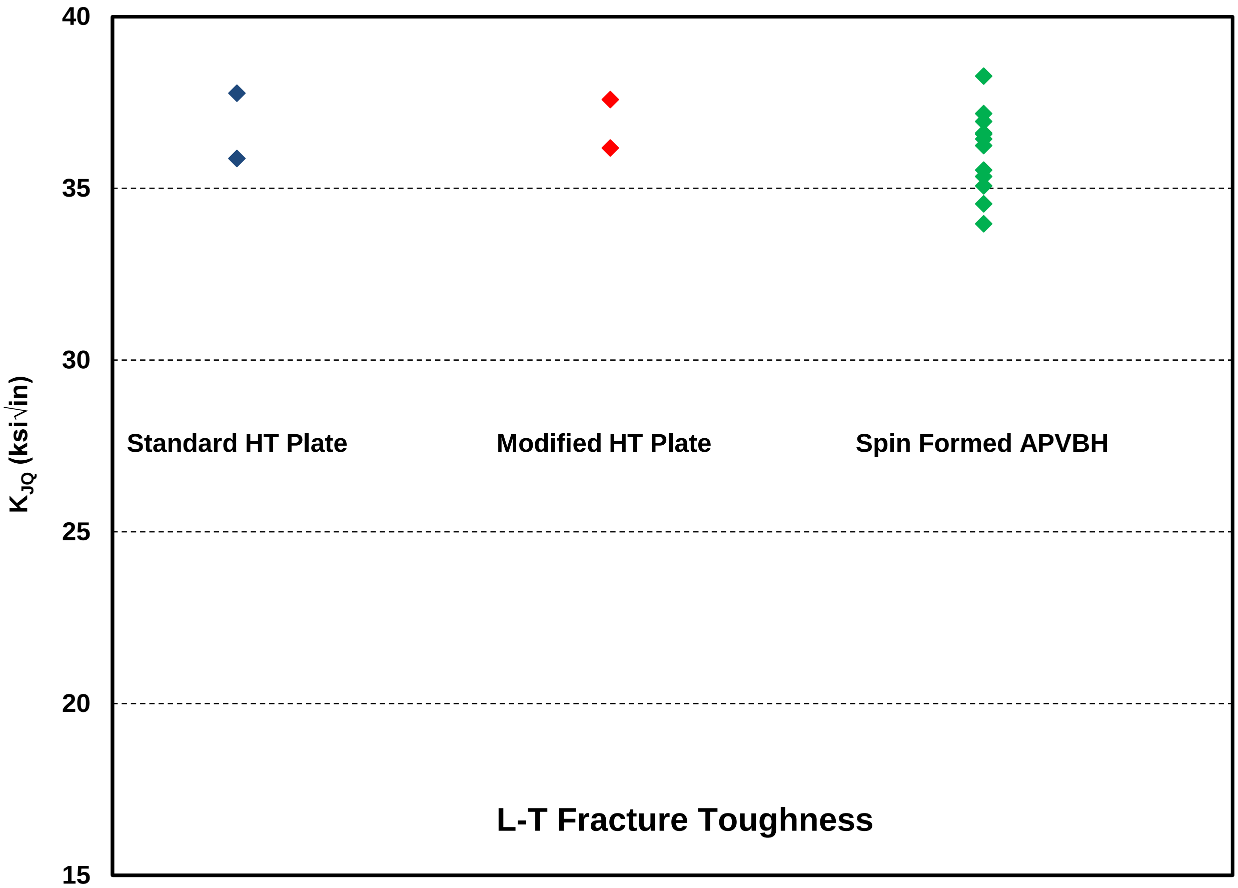


Figure 31. Fracture toughness of standard and modified heat treat wrought plate vs. spin formed aft bulkhead; L-T orientation.

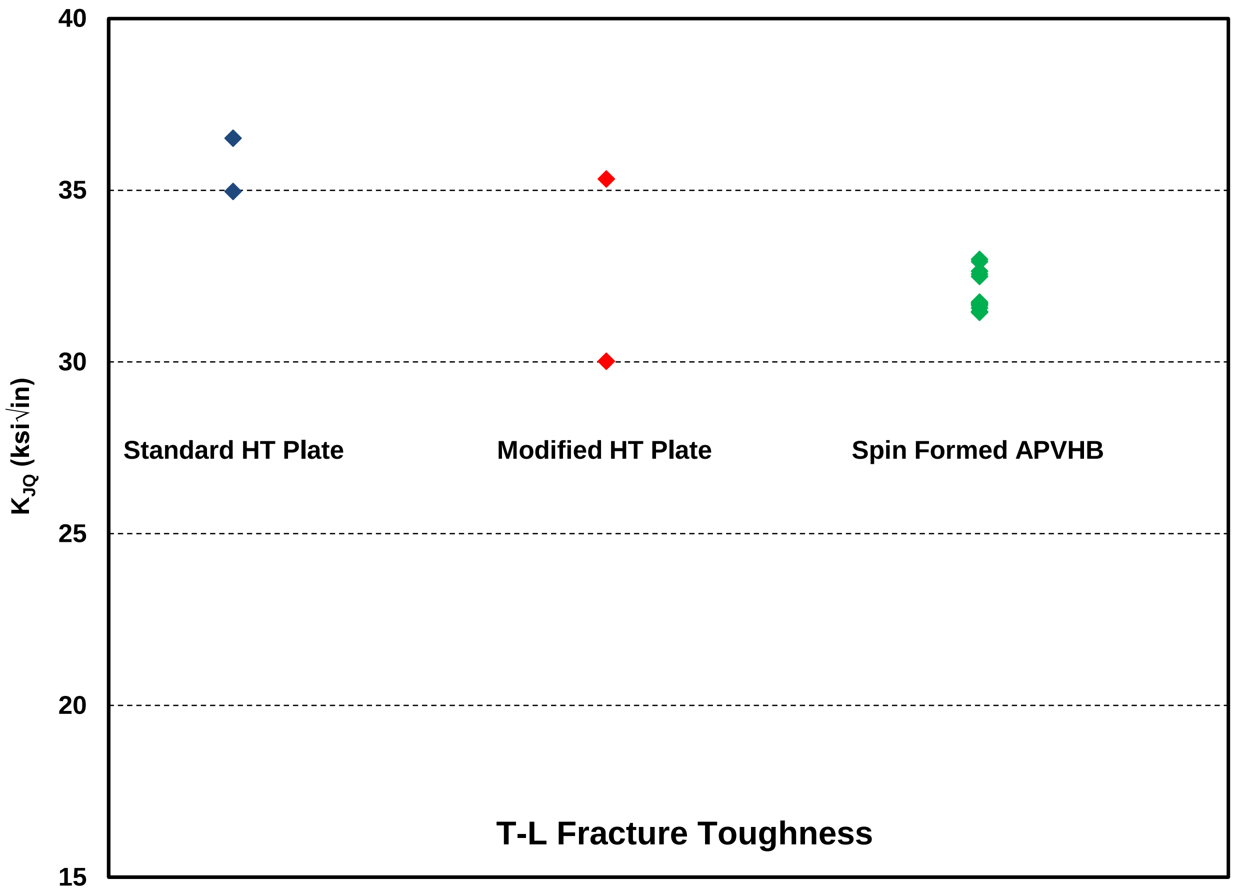


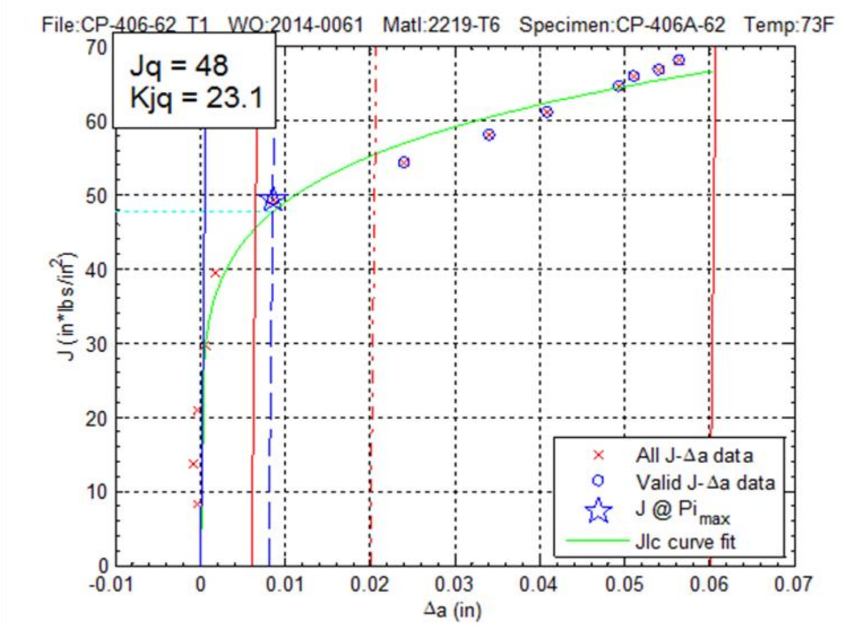
Figure 32. Fracture toughness of standard and modified heat treat wrought plate vs. spin formed aft bulkhead; T-L orientation.

7.2.4 Comparison with Other Al 2219-T62 Spin Formed Product

All of the data for the CPST dome exhibited rising R-curve behavior, indicative of stable tearing capability as shown in the typical R-curve presented in Figure 33. This behavior is consistent with the R-curve behavior exhibited by material from the spin formed aft bulkhead. The aft bulkhead and CPST dome were fabricated by Spincraft and received the modified heat treatment.

Fracture toughness data in the S-T orientation from the CPST dome is compared to fracture toughness data from the original study on the spin formed aft bulkhead (3) in Figure 34. Individual test results from the spin formed aft bulkhead are shown for coupon blanks near the rim (M3); membrane (M2, M5, and M6); and pole (M1 and M4). (See aft bulkhead cut plan shown in Figure 27 for location of coupon blanks.) The S-T fracture toughness measured at the rim location in the CPST dome was higher than that for the pole, based on average and individual test results. A similar trend was observed in the aft bulkhead, but the change in toughness from pole to rim was less in magnitude than in the CPST dome. Based on average

values, toughness at the rim was similar for both products, but the toughness at the pole was slightly lower for the CPST dome than the aft bulkhead. Differences in toughness behavior with location may be due to variations in spin forming deformation and grain size. Material from the CPST dome was not available for a detailed forming or microstructural assessment, so a conclusive explanation for the fracture toughness differences would require further study. It should be noted that while the aft bulkhead and CPST dome were produced by Spincraft differences in size, shape, and thickness will affect the deformation imparted to the material and consequently material properties. In addition, during examination of the SCC specimens it was noted that the grain size in the CPST dome was visually larger than that for the aft bulkhead, which may have contributed to the differences in toughness behavior.



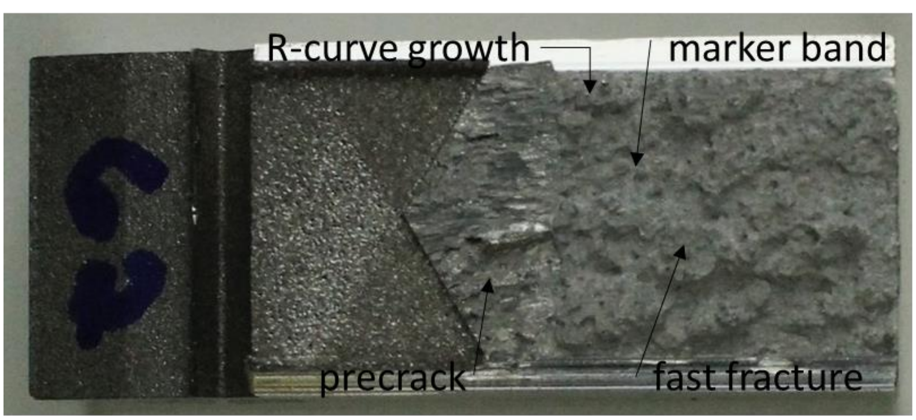


Figure 33. ***J-R curve and fracture surface of specimens CP-406A-62 from the pole region of the Al 2219-T62 spin formed CPST dome; S-T orientation.***

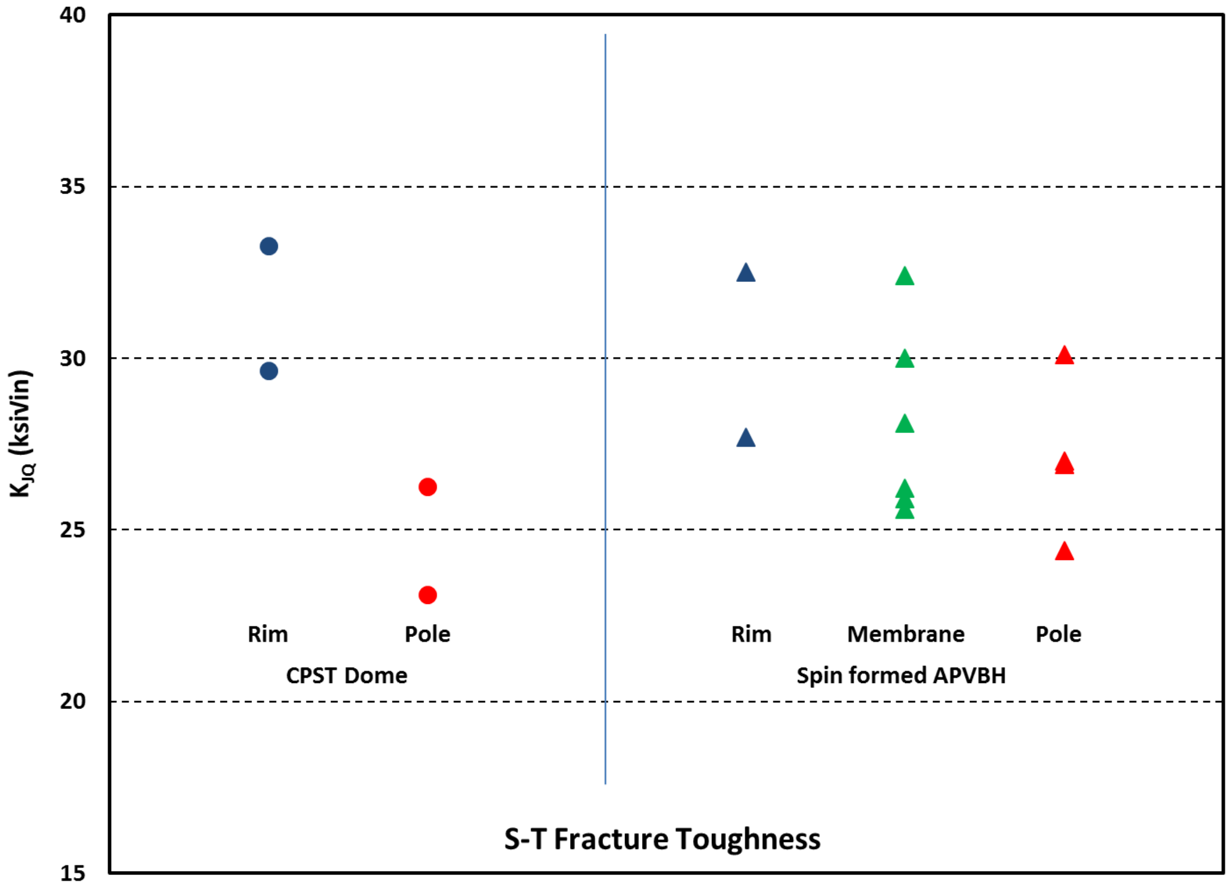


Figure 34. Fracture toughness of spin formed CPST dome vs. aft bulkhead; S-T orientation.

7.3 Fracture Toughness Summary

Spin form fabrication did not have adverse effects on the fracture behavior of the material. The aft bulkhead fracture toughness values and fracture behavior were consistent with the behavior of the Al 2219-T62 wrought plate processed using the standard and modified heat treatments. The supplementary fracture toughness tests of the wrought plate showed room temperature in-plane toughness values ranged from 31 to 38 ksi√in. The material was capable of stable crack extension and exhibited rising R-curve behavior. There was little to no difference in fracture behavior with heat treat variant. In comparison, the in-plane (L-T and T-L) toughness values for the aft bulkhead ranged from 31.5 to 38.3 ksi√in, and the material exhibited rising R-curve behavior.

The supplementary fracture toughness tests of the spin formed CPST dome showed that the S-T toughness was similar to the aft bulkhead toughness. The trends observed with location were similar in both products with toughness higher near the rim than the pole. Toughness values were similar for both products near the pole and toughness was slightly lower in the CPST dome near the rim. Differences in toughness values between the CPST dome and aft bulkhead may be

due to differences in the level of deformation imparted which arise due to differences in size, shape, and thickness of the two products. Toughness in the S-T orientation was greater than or equal to 23 ksi√in for the CPST dome, and 27 ksi√in for the aft bulkhead. Both products exhibited rising R-curve behavior indicative of stable tearing capability. The positive fracture toughness attributes from the CPST dome, a comparable product form to the aft bulkhead, give further credence to the spin forming process as a viable fabrication process for MPCV aft bulkhead.

The following findings are provided in response to the questions posed in Table 19 for the supplemental fracture toughness tests.

F-9. The fracture toughness of the aft bulkhead was comparable to the standard and modified plates.

F-10. Fracture toughness of the standard and modified plates was essentially equivalent indicating that there was no adverse effect of the slower quench rate used during processing.

F-11. Fracture toughness of the aft bulkhead and CPST dome were equivalent and exhibited overall average toughness values of 25 ksi√in and stable tearing.

8.0 Findings, Observations, and NESC Recommendations

The following findings, observations, and NESC recommendations are based on the results of a supplemental study for which the main objective was to determine whether there are technical obstacles relative to the spin forming a single piece aft bulkhead.

The Phase II M&P studies did not identify any potential insurmountable technical issues that would preclude spin forming the MPCV aft bulkhead. The potential benefits of spin forming an Al 2219 aft bulkhead include reduced weight and production costs, which are associated with eliminating welds and weld lands, and improved performance and design margins.

8.1 Findings

The following findings are provided in response to the questions posed in Table 19 for the supplemental tests:

F-1. A retest of coupon blank M10 showed that the single specimen failure at 50% YS exposure stress was not repeatable.

- Material from coupon blank M10 and the adjacent blank, J2, passed the 30-day 3.5% NaCl alternate immersion exposure at 50%YS exposure stress and had acceptable residual strength ratios.
- Post-exposure microstructural examination showed SCC in both the Phase II tests of coupon blank M10 and the supplemental tests of coupon blank M10 and J2.

F-2. Aft bulkhead material from coupon blank M10 passed the 30-day 3.5% NaCl alternate immersion exposure at exposure stress levels based on MMPDS for plate and measured ST YS values for the aft bulkhead.

F-3. Material from additional locations in the aft bulkhead passed the 30-day 3.5% NaCl alternate immersion exposure at exposure stress levels based on MMPDS YS values for plate and exhibited residual strengths above minimum required values.

- Residual strength values were higher at the rim as compared with the pole and membrane locations.

F-4. The combined spin forming process and associated modified heat treat practice reduces the SCC resistance compared with wrought plate, likely related to the slower quench rate associated with the modified heat treatment.

- While no SCC failures occurred during 30-day alternate immersion exposure in a 3.5% NaCl environment, post-exposure metallurgical evaluation showed SCC in the spin formed aft bulkhead and CPST dome materials subjected to the modified heat treatment.
- Remnant plate processed using the modified heat treatment exhibited lower post-exposure residual strength values than standard plate.

- Post-exposure metallurgical evaluation showed SCC in the modified plate. No evidence of SCC was found in the standard plate.

F-5. The SCC resistance of the Al 2219-T62 spin formed aft bulkhead and CPST dome were similar indicating that the SCC behavior observed is likely representative of similarly processed Al 2219-T62 spin formed products.

F-6. Tensile properties of the aft bulkhead were uniform with through-thickness position and orientation and were not adversely affected by the inhomogeneous microstructure

- Tensile strengths varied less than 5% with through-thickness position and specimen orientation, with strengths higher by 2 to 3 ksi at the t/8 position.

F-7. Tensile properties of the aft bulkhead were equivalent to the standard and modified plates indicating that there was no adverse effect of the slower quench rate used during processing.

F-8. Tensile properties in the ST orientation were higher than that for the L and LT orientations in both the aft bulkhead and modified plate indicating that this trend is inherent to the plate used in fabrication of the aft bulkhead and not a result of the spin forming process.

F-9. The fracture toughness of the aft bulkhead was comparable to the standard and modified plates.

F-10. Fracture toughness of the standard and modified plates was essentially equivalent indicating that there was no adverse effect of the slower quench rate used during processing.

F-11. Fracture toughness of the aft bulkhead and CPST dome were equivalent and exhibited overall average toughness values of 25 ksi√in and stable tearing.

8.2 Observations

The following observations were identified:

O-1. The SCC data for the aft bulkhead provides insight about the SCC resistance of the spin formed Al 2219-T62 material, but is insufficient to establish a SCC threshold stress level.

- Testing in this study sampled one spin formed aft bulkhead and one material lot. Establishing a threshold requires testing of multiple serial production aft bulkheads and multiple material lots.
- Evidence of SCC was observed for all non-zero exposure stress levels indicating that the SCC threshold is below the minimum stress level used in this study.

O-2. Grain size in the CPST dome was larger than in the aft bulkhead, which may have contributed to a greater extent of pitting and lower percent tensile strength retained and residual strength ratios.

O-3. The higher tensile properties noted at the t/8 through-thickness position compared to the t/2 and 7t/8 positions may be related to the smaller grain size observed at that location.

8.3 NESC Recommendations

The following NESC recommendations were identified and directed towards the MPCV Program:

R-1. Perform additional SCC testing on spin formed Al 2219-T6 products to establish a threshold stress level for SCC and to determine a maximum allowable service stress. ***(O-1)***

- Additional testing should be performed on multiple articles from initial serial production and should sample multiple material lots.
- Exposure stress levels should be successively reduced until there is no evidence of stress corrosion.

R-2. Perform heat treatment studies to determine whether a faster quench rate can be achieved that improves SCC resistance without compromising residual stress and distortion control. ***(F-4)***

9.0 Acronyms List

a	Crack Length
AMA	Analytical Mechanics Associates
AMS	Aerospace Material Specifications
ASTM	American Society for Testing and Materials
C(T)	Compact Tension
CPST	Cryogenic Propellant Storage and Transfer
e, e_{total}	Elongation, %
E	Modulus of Elasticity
EBSD	Electron Backscatter Diffraction
EFT-1	Exploration Flight Test
EM-1	Exploration Mission
FPVBH	Forward Pressure Vessel Bulkhead
GL	Gage Length
IML	Inner Mold Line
in	Inch
ipm	Inches Per Minute
J_q	Provisional J Integral
J	J Integral
K	Crack Tip Stress Intensity, ksi$\sqrt{\text{in}}$
K_{JQ}	Provisional Fracture Toughness
ksi	Kilopound Per Square Inch, 10^3

L	Longitudinal (direction parallel to plate rolling direction)
LaRC	Langley Research Center
LM	Lockheed Martin
LT, T	Long Transverse (direction perpendicular to the longitudinal (rolling) direction and in the rolling plane)
M&P	Materials and Processes
MMPDS	Metallic Material Properties Development and Standardization
MPCV	Multi-Purpose Crew Vehicle
MSFC	Marshall Space Flight Center
Msi	Megapound Per Square Inch, 10^6
MUA	Materials Usage Agreement
NaCl	Sodium Chloride
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
OML	Outer Mold Line
psi	Pounds Per Square Inch
R-curve	Resistance Curve
S, ST	Short Transverse (through-thickness direction of the plate perpendicular to both longitudinal and long transverse directions)
SCC	Stress Corrosion Crack
SLS	Space Launch System
t	Thickness
UTS	Ultimate Tensile Strength
UTS_f	Residual Strength of the Exposed Specimen
UTS_i	Average Ultimate Tensile Strength for the Unexposed Specimens
UTS_o	Averaged Residual Strength of Non-Stressed and Exposed Specimens
UTS_s	Residual Strength of Stressed and Exposed Specimen
YS	Yield Strength
σ	Average Linear Stress
ε	Average Linear Strain

10.0 References

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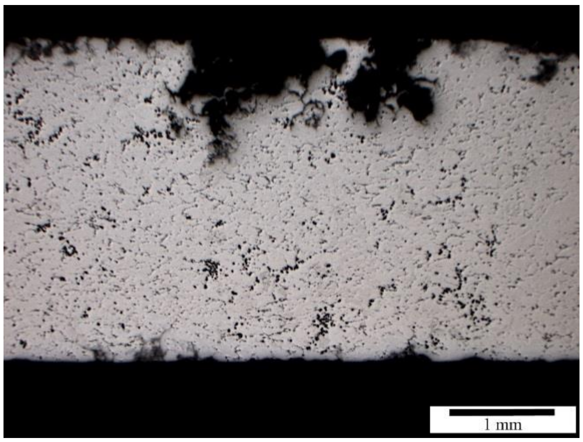
11.0 Appendices

11.1 Appendix A: Photomicrographs of Specimens from the Phase II Stress Corrosion Tests; LT Orientation



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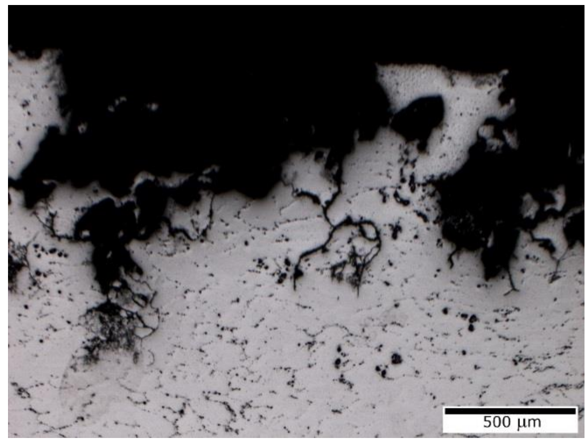

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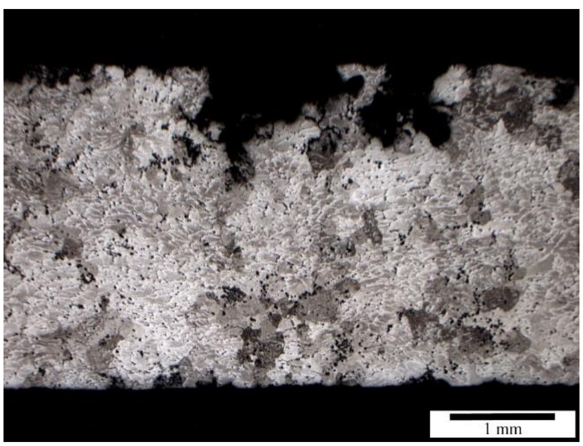

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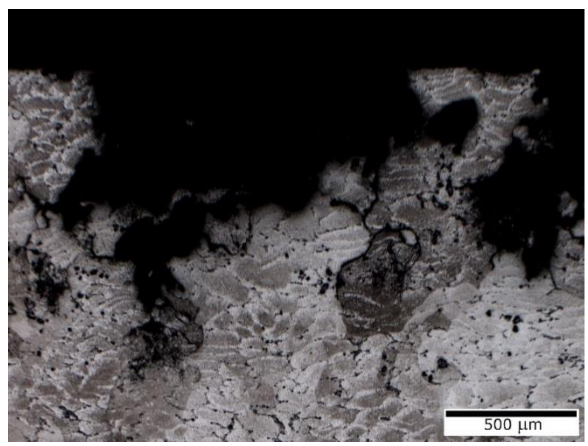

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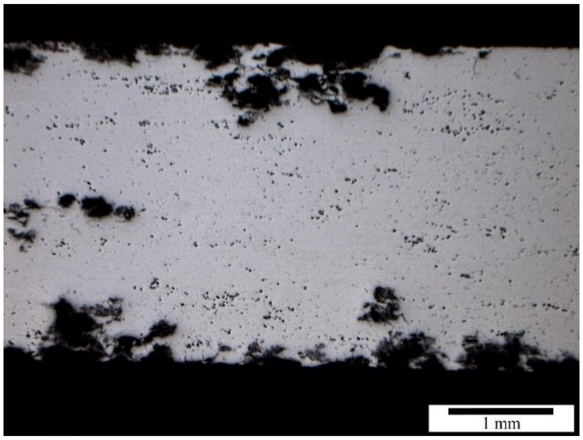
Coupon blank:	M7
Specimen No.:	2
Orientation:	LT
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

(a) 0% YS



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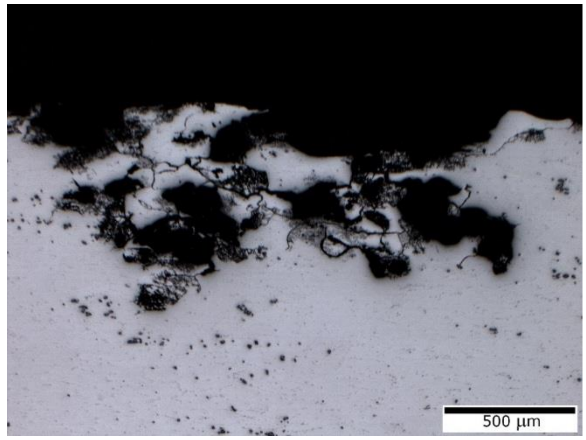

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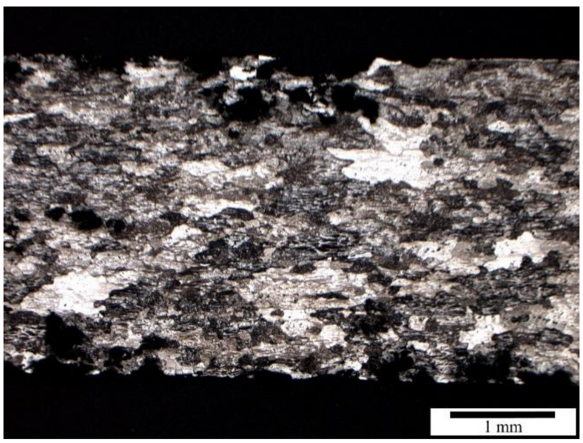

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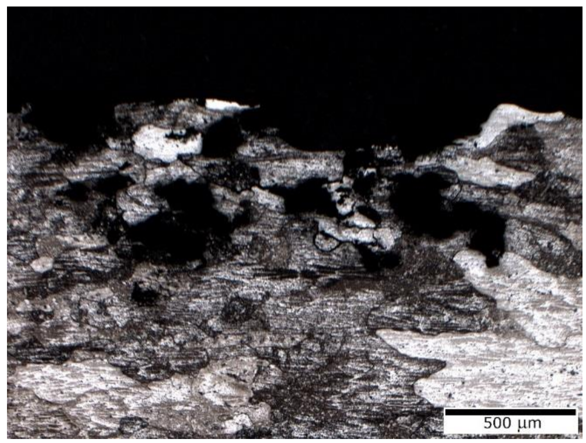

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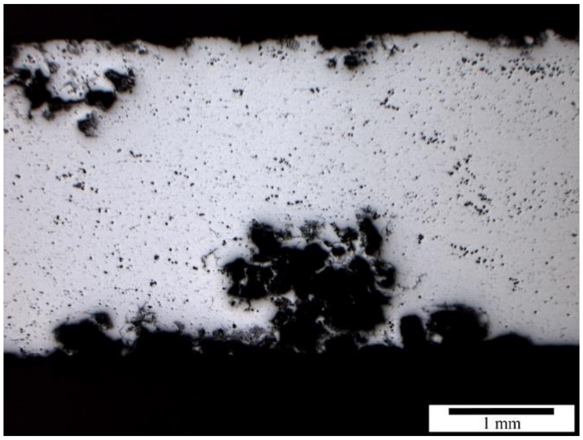
Coupon blank:	M7
Specimen No.:	5
Orientation:	LT
Applied stress (% YS):	50, based on M7 average LT YS
Applied stress (ksi):	18.32
Failed?:	No
SCC?:	No

(b) 50% YS



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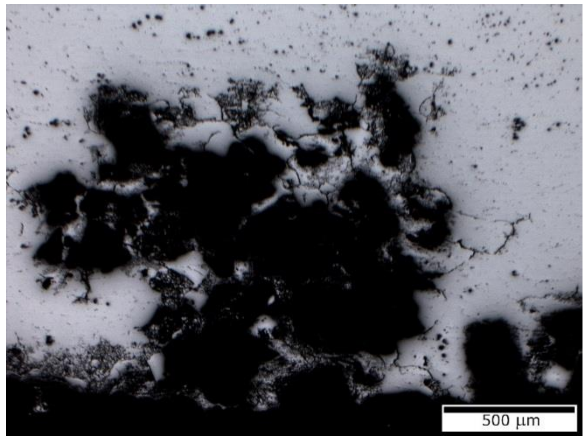

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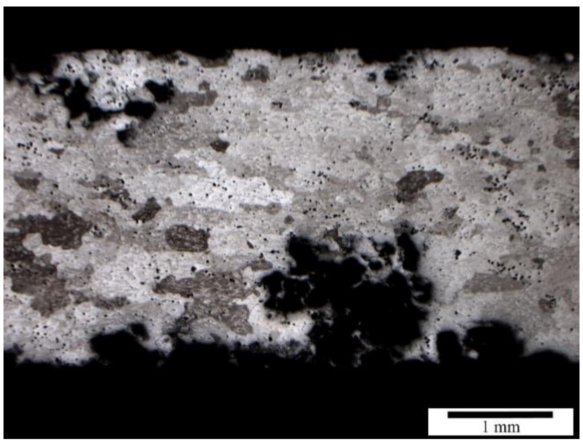

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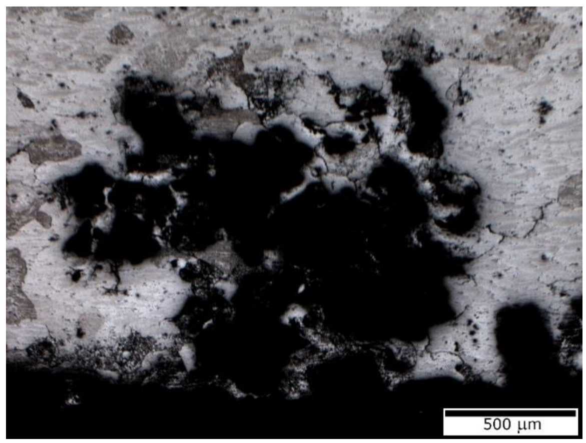

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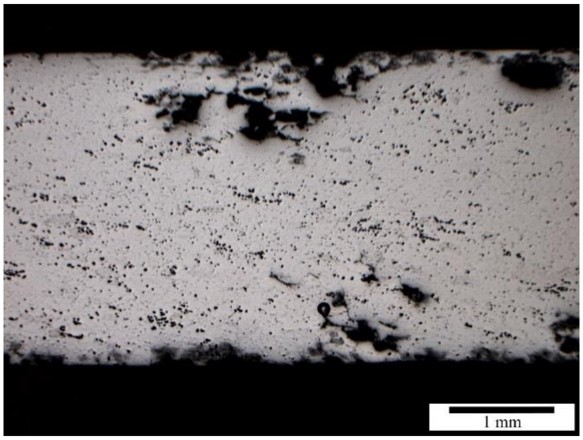
Coupon blank:	M7
Specimen No.:	8
Orientation:	LT
Applied stress (% YS):	75, based on M7 average LT YS
Applied stress (ksi):	27.48
Failed?:	No
SCC?:	No

(c) 75% YS



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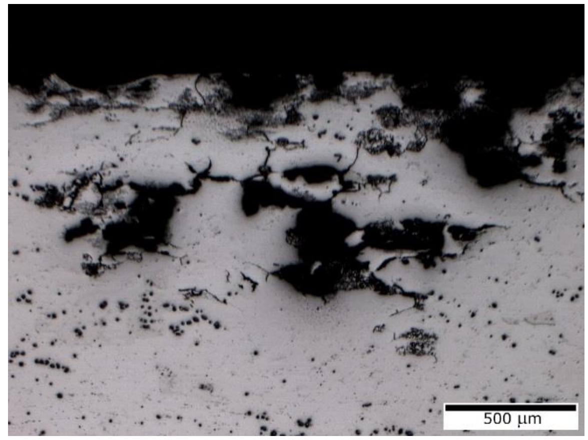

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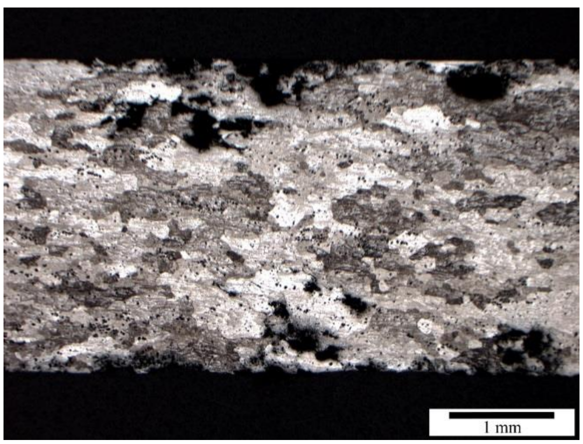

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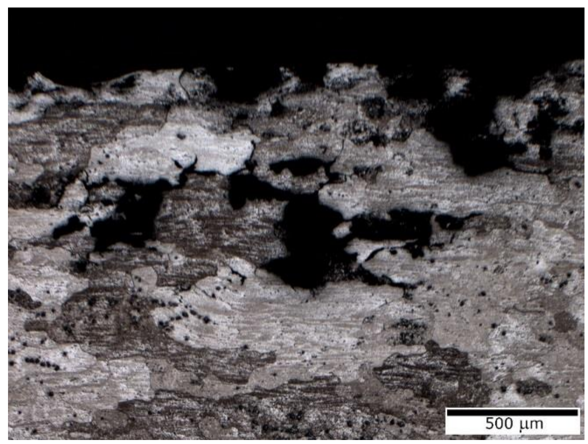

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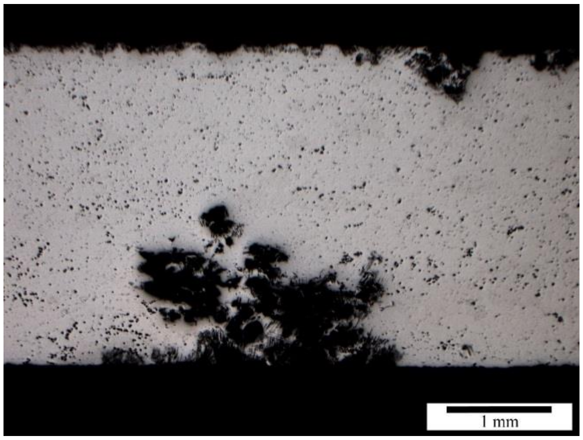
Coupon blank:	M7
Specimen No.:	12
Orientation:	LT
Applied stress (% YS):	90, based on M7 average LT YS
Applied stress (ksi):	32.98
Failed?:	No
SCC?:	No

(d) 90% YS

Figure A-1. Photomicrographs of SCC specimens from aft bulkhead coupon blank M7 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; (c) 75% YS; and (d) 90% YS.



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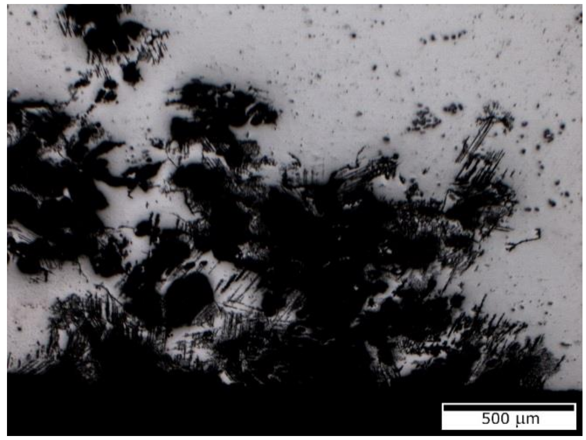

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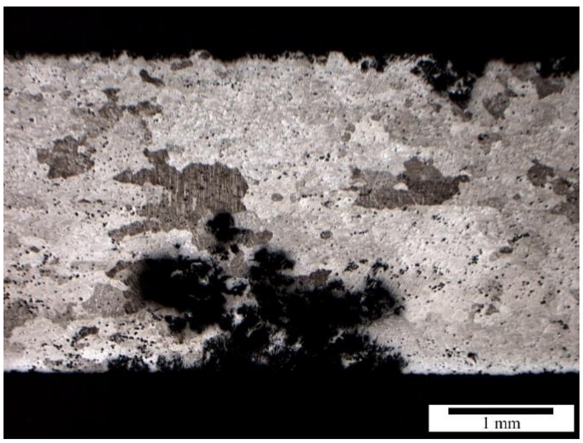

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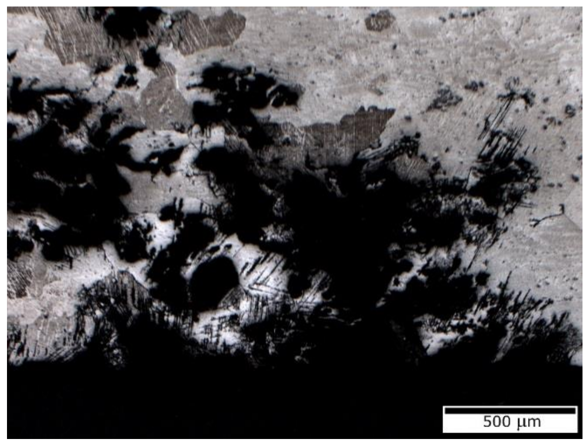

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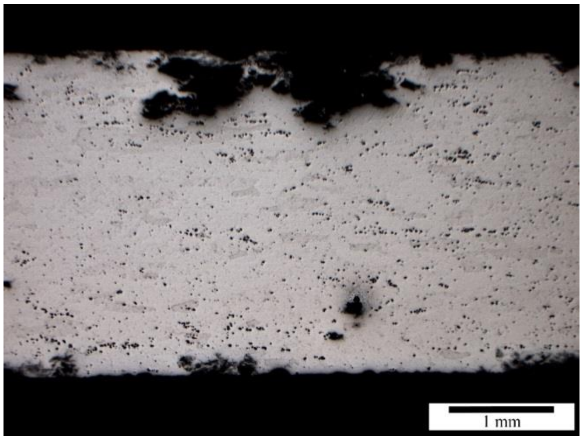
Coupon blank:	M8
Specimen No.:	44
Orientation:	LT
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

(a) 0% YS



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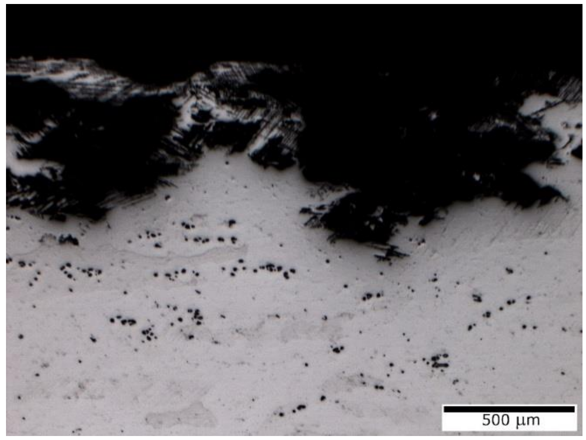

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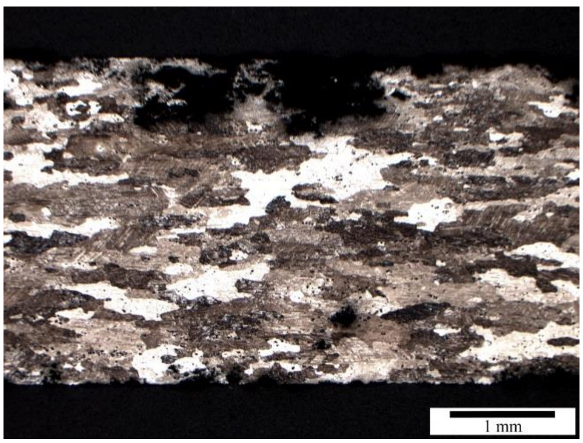

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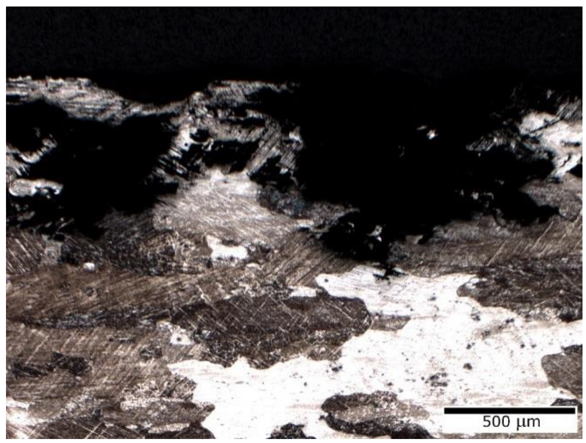

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Coupon blank:	M8
Specimen No.:	47
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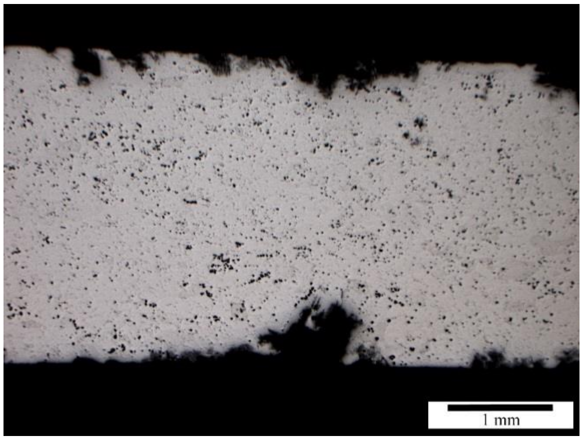
Applied stress (ksi):	19.39
Failed?:	No
SCC?:	No

(b) 50% YS



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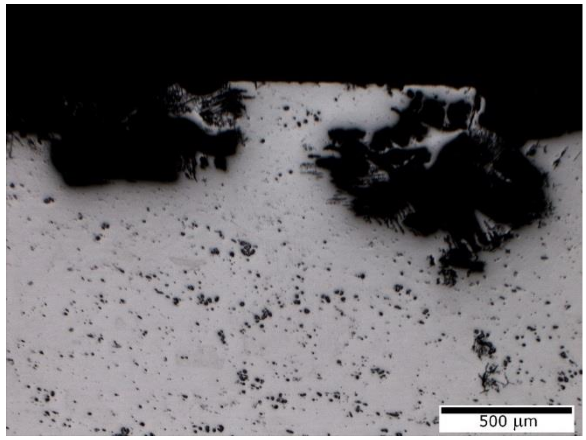
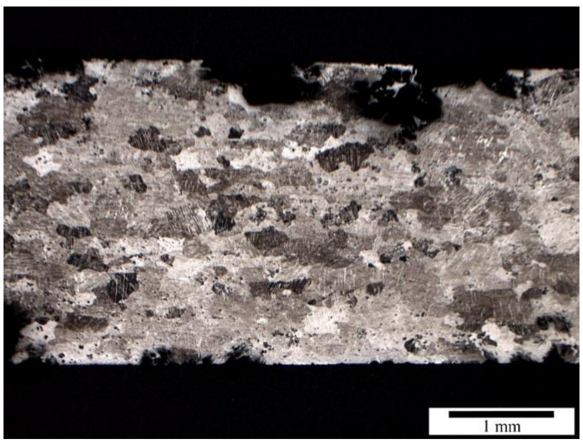
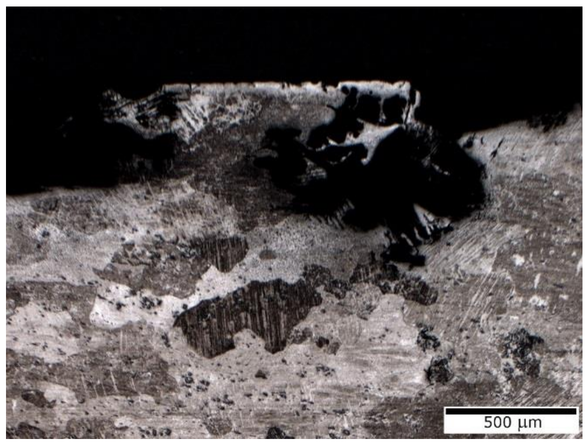


#50_unetched_m02_50x.jpg



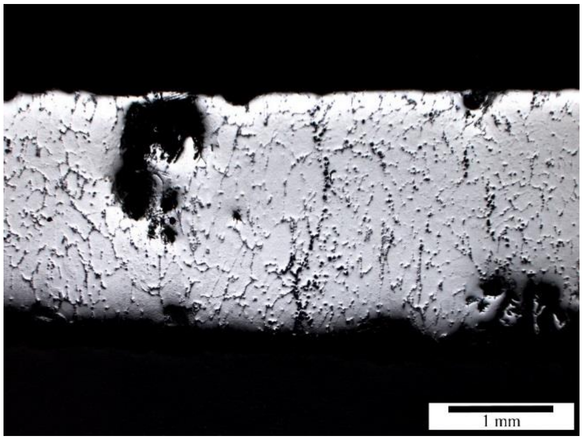
#50_etched_m03_20x.jpg



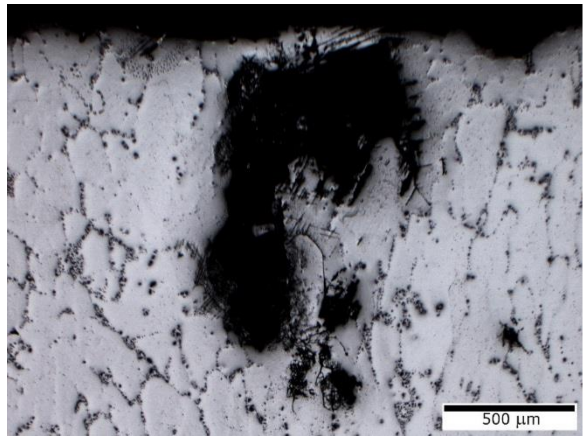
#50_etched_m04_50x.jpg

Coupon blank:	M8
Specimen No.:	50
Orientation:	LT
Applied stress (% YS):	75, based on M8 average LT YS
Applied stress (ksi):	29.90
Failed?:	No
SCC?:	No

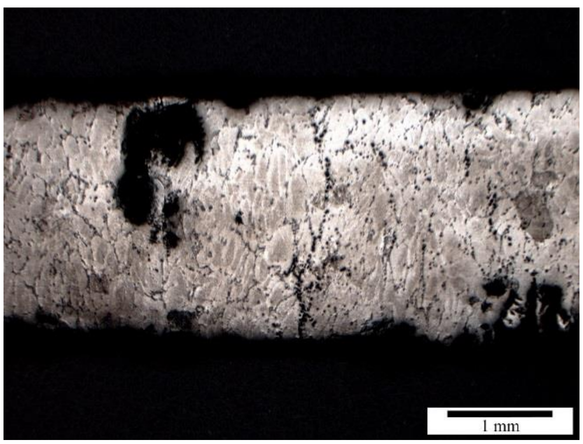
(c) 75% YS



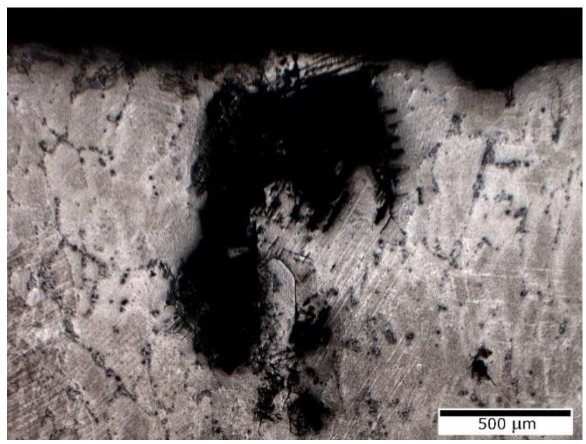
#54_unetched_m01_20x.jpg



#54_unetched_m02_50x.jpg



#54_etched_m03_20x.jpg

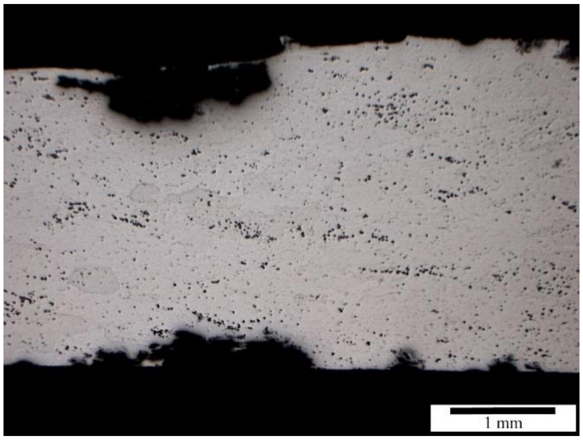


#54_etched_m04_50x.jpg

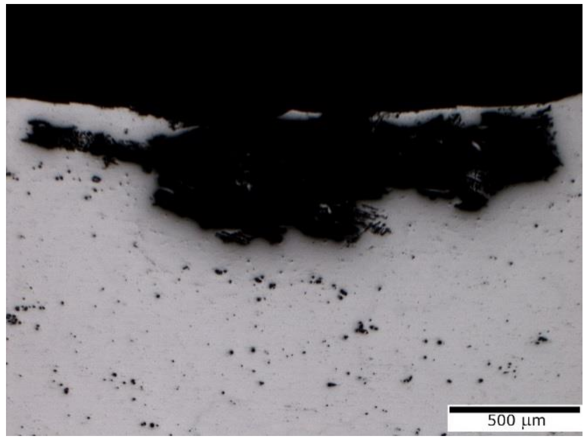
Coupon blank:	M8
Specimen No.:	54
Orientation:	LT
Applied stress (% YS):	90, based on M8 average LT YS
Applied stress (ksi):	34.90
Failed?:	No
SCC?:	No

(d) 90% YS

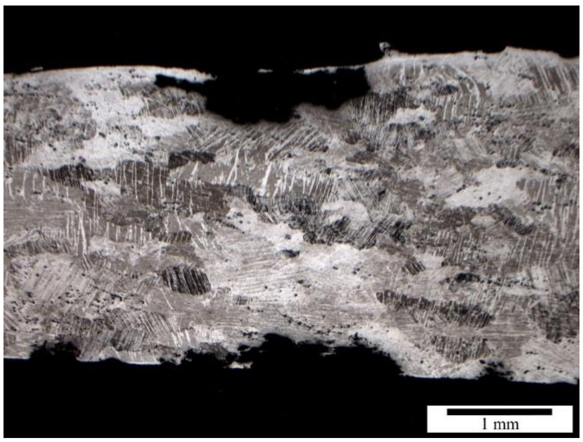
Figure A-2. Photomicrographs of SCC specimens from aft bulkhead coupon blank M8 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; (c) 75% YS; and (d) 90% YS.



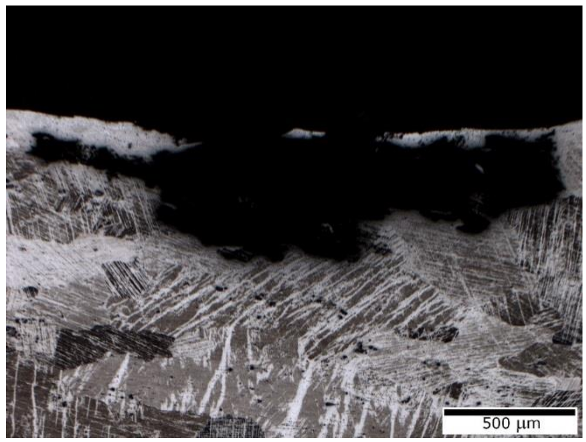
#86_unetched_m01_20x.jpg



#86_unetched_m02_50x.jpg



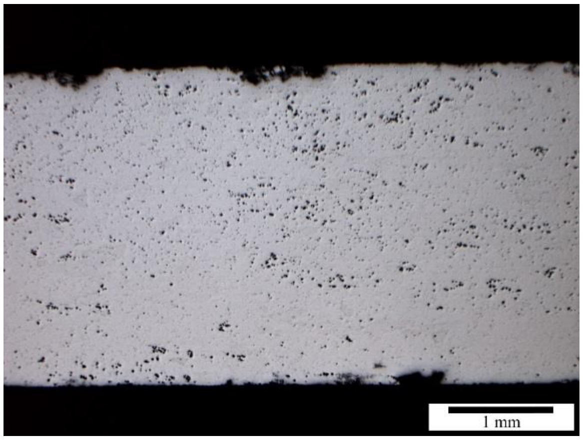
#86_etched_m03_20x.jpg



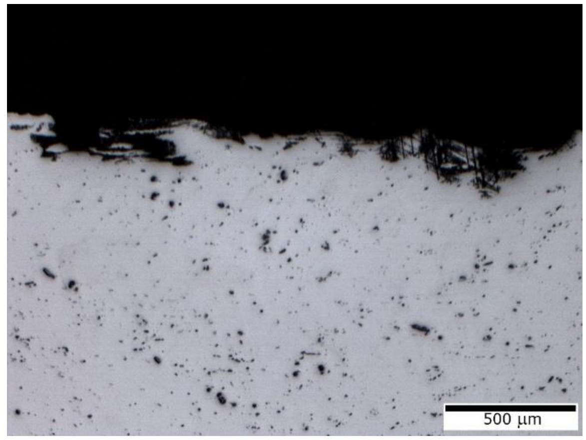
#86_etched_m04_50x.jpg

Coupon blank:	M9
Specimen No.:	86
Orientation:	LT
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

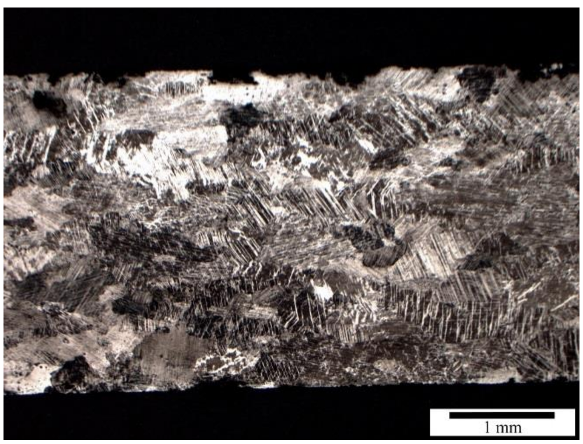
(a) 0% YS



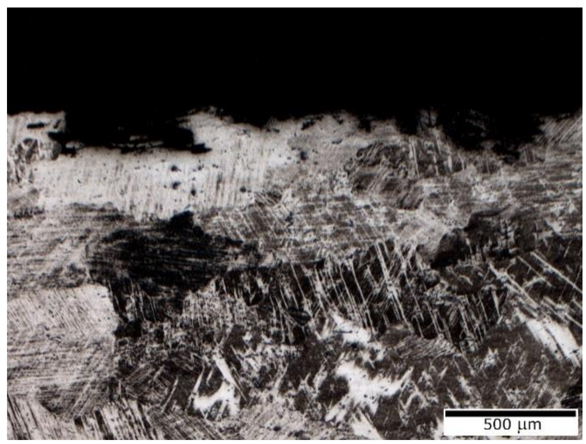
#89_unetched_m01_20x.jpg



#89_unetched_m02_50x.jpg



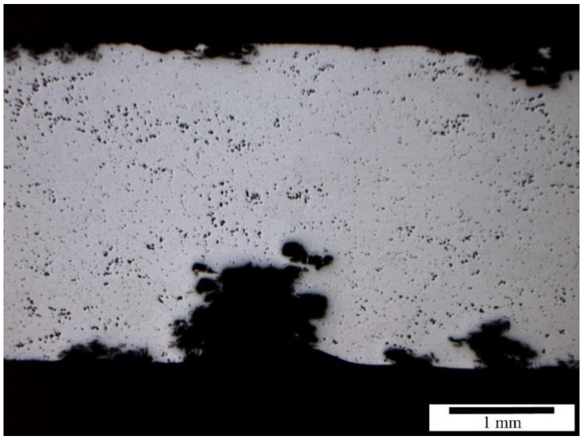
#89_etched_m03_20x.jpg



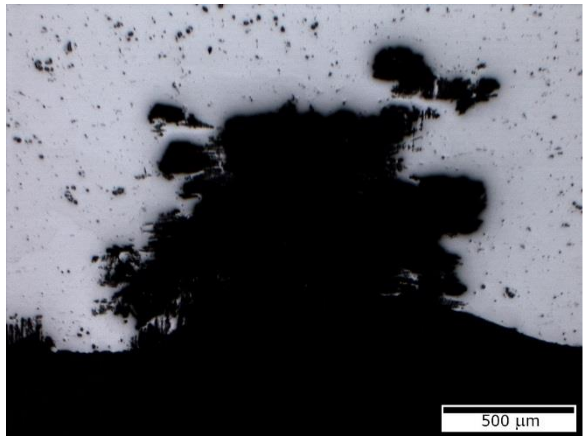
#89_etched_m04_50x.jpg

Coupon blank:	M9
Specimen No.:	89
Orientation:	LT
Applied stress (% YS):	50, based on M9 average LT YS
Applied stress (ksi):	19.84
Failed?:	No
SCC?:	No

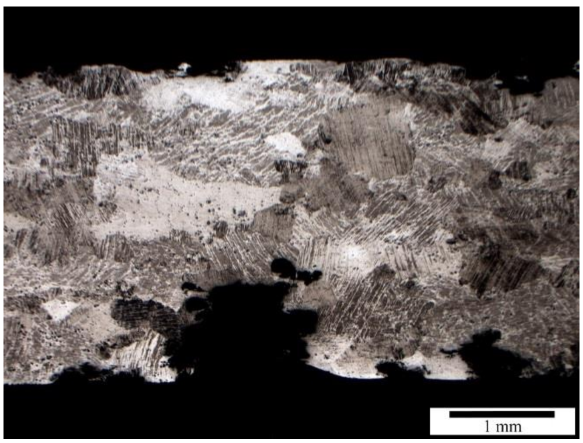
(b) 50% YS



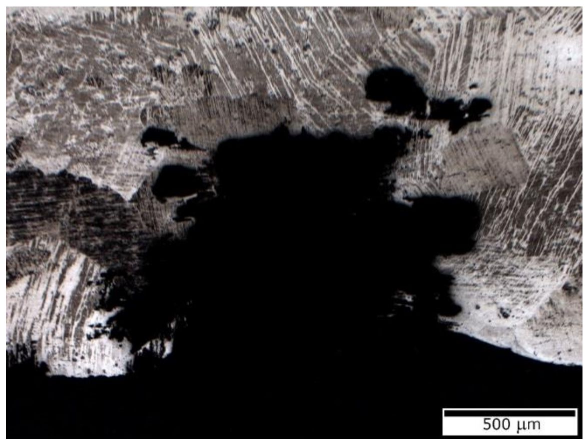
#92_unetched_m01_20x.jpg



#92_unetched_m02_50x.jpg



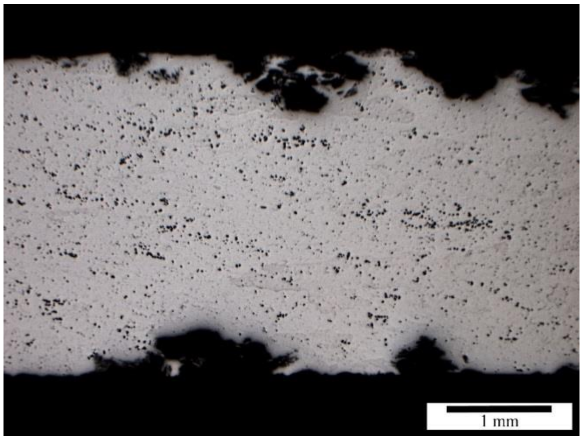
#92_etched_m03_20x.jpg



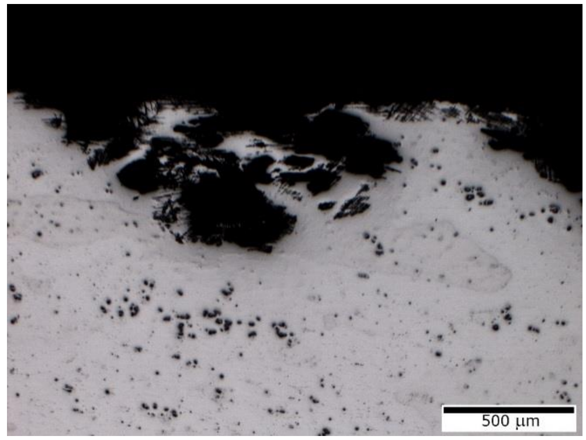
#92_etched_m04_50x.jpg

Coupon blank:	M9
Specimen No.:	92
Orientation:	LT
Applied stress (% YS):	75, based on M9 average LT YS
Applied stress (ksi):	29.76
Failed?:	No
SCC?:	No

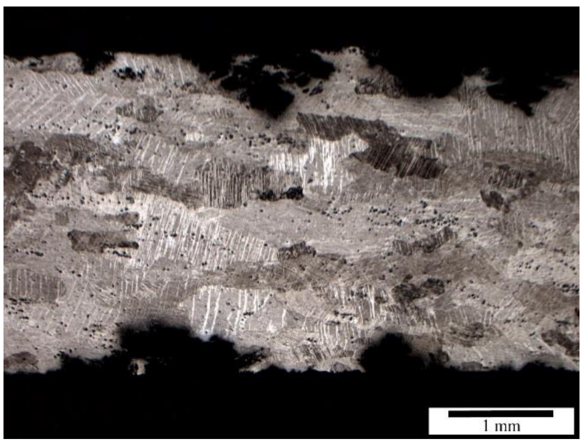
(c) 75% YS



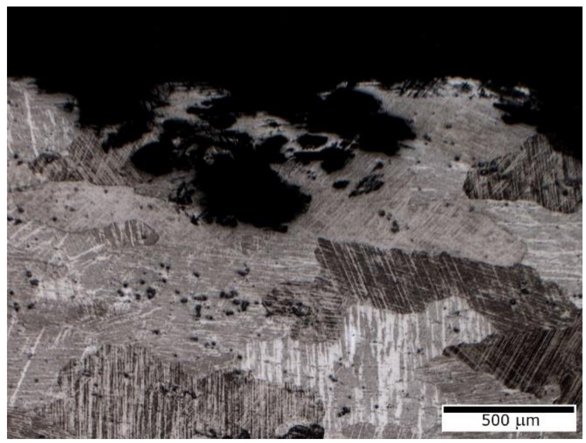
#96_unetched_m01_20x.jpg



#96_unetched_m02_50x.jpg



#96_etched_m03_20x.jpg

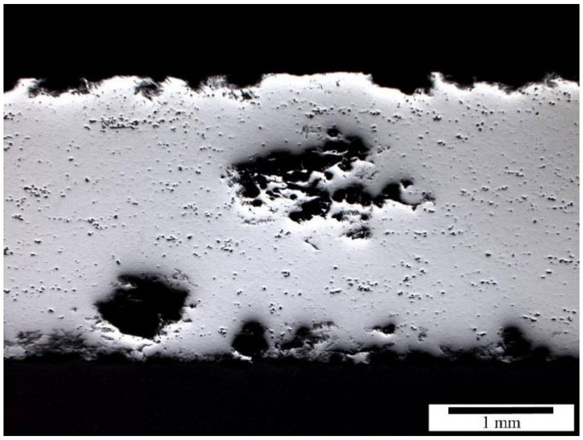


#96_etched_m04_50x.jpg

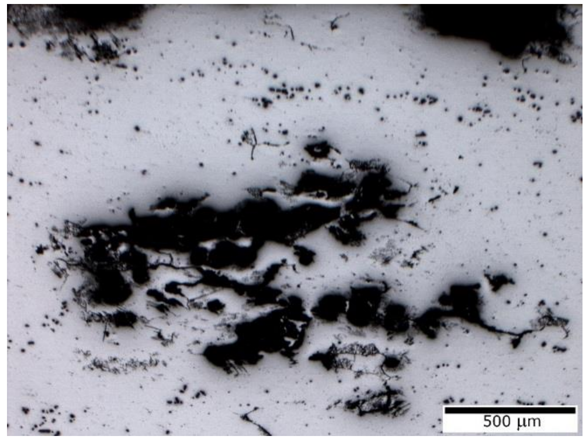
Coupon blank:	M9
Specimen No.:	96
Orientation:	LT
Applied stress (% YS):	90, based on M9 average LT YS
Applied stress (ksi):	35.71
Failed?:	No
SCC?:	No

(d) 90% YS

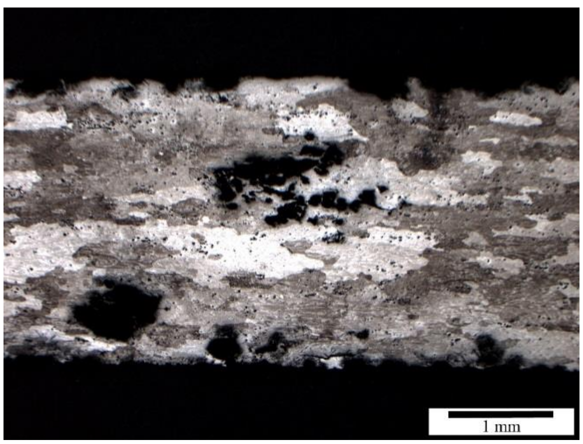
Figure A-3. ***Photomicrographs of SCC specimens from aft bulkhead coupon blank M9 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; (c) 75% YS; and (d) 90% YS.***



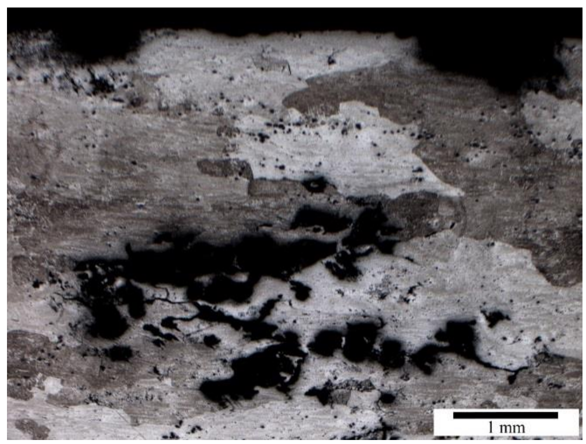
#170_unetched_m01_20x.jpg



#170_unetched_m02_50x.jpg



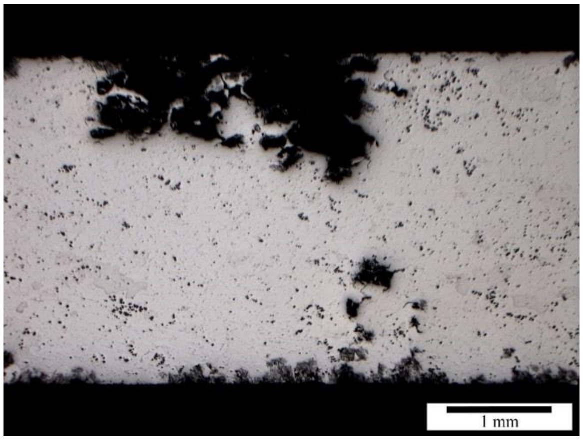
#170_etched_m03_20x.jpg



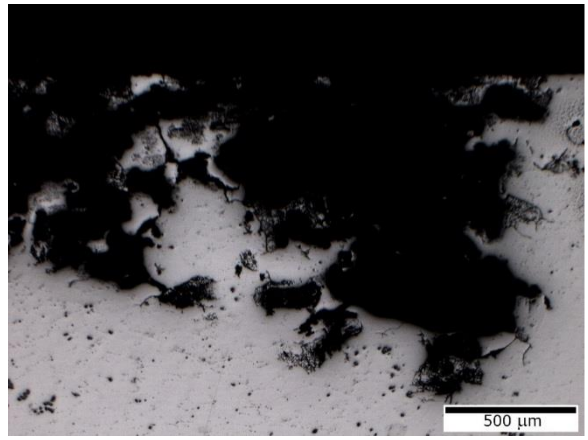
#170_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	170
Orientation:	LT
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

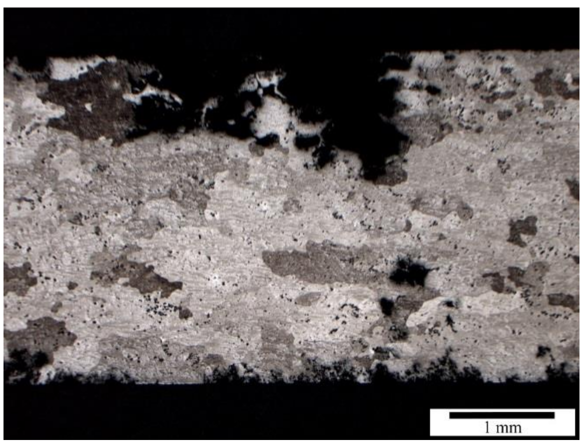
(a) 0% YS



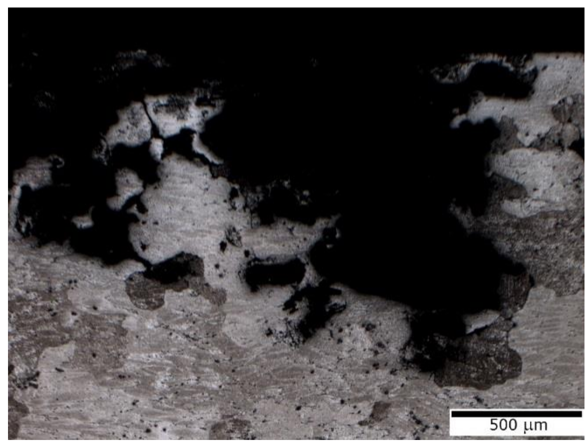
#173_unetched_m01_20x.jpg



#173_unetched_m02_50x.jpg



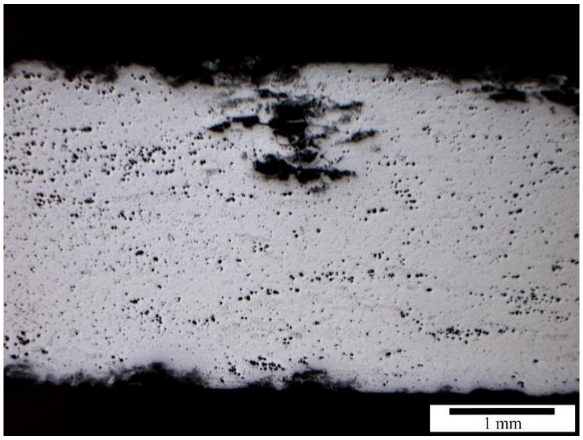
#173_etched_m03_20x.jpg



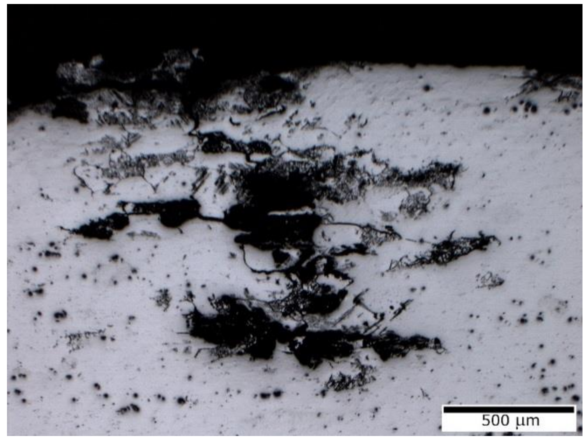
#173_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	173
Orientation:	LT
Applied stress (% YS):	50, based on M10 average LT YS
Applied stress (ksi):	18.94
Failed?:	No
SCC?:	No

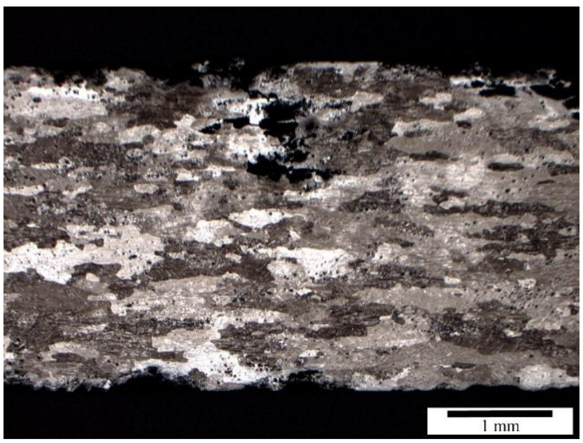
(b) 50% YS



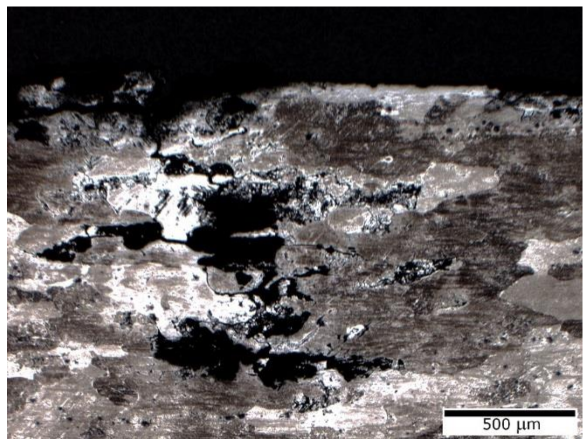
#176_unetched_m01_20x.jpg



#176_unetched_m02_50x.jpg



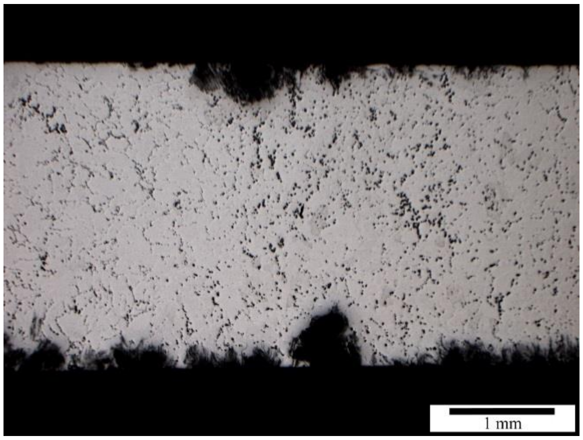
#176_etched_m03_20x.jpg



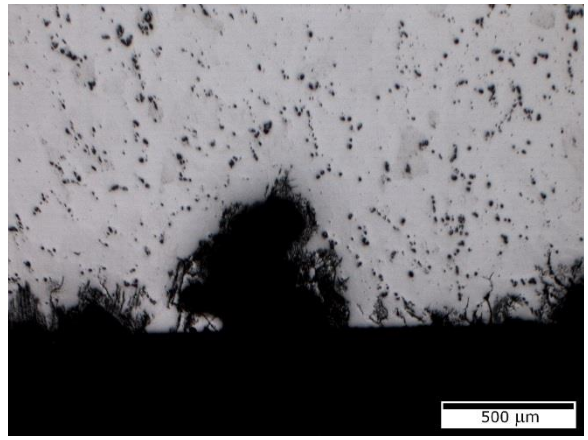
#176_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	176
Orientation:	LT
Applied stress (% YS):	75, based on M10 average LT YS
Applied stress (ksi):	28.40
Failed?:	No
SCC?:	No

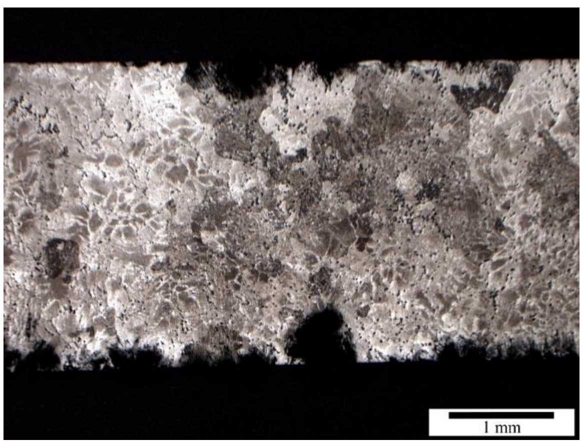
(c) 75% YS



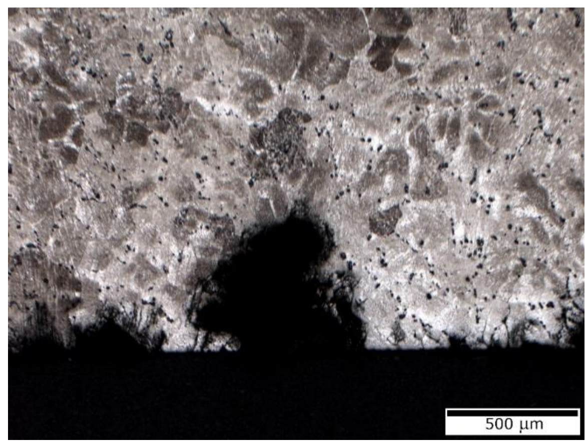
#180_unetched_m01_20x.jpg



#180_unetched_m02_50x.jpg



#180_etched_m03_20x.jpg



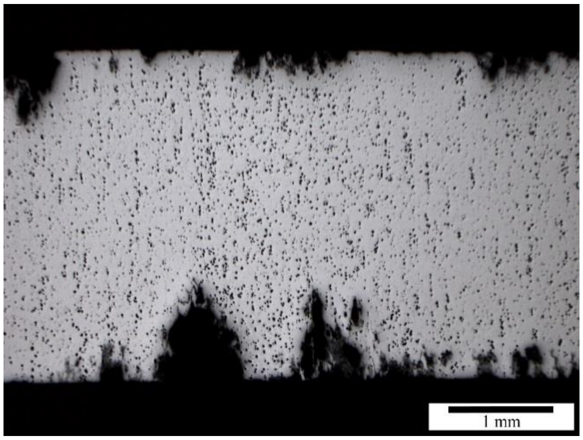
#180_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	180
Orientation:	LT
Applied stress (% YS):	90, based on M10 average LT YS
Applied stress (ksi):	34.08
Failed?:	No
SCC?:	No

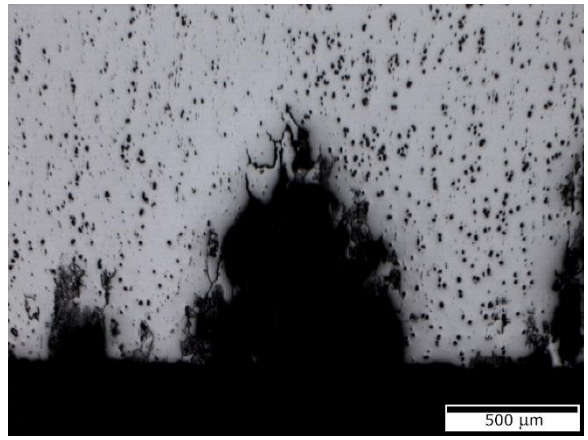
(d) 90% YS

Figure A-4. ***Photomicrographs of SCC specimens from aft bulkhead coupon blank M10 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; (c) 75% YS; and (d) 90% YS.***

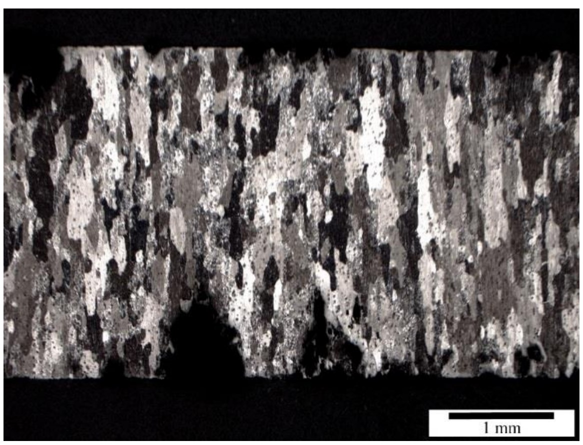
11.2 Appendix B: Photomicrographs of Specimens from the Phase II Stress Corrosion Tests; ST Orientation



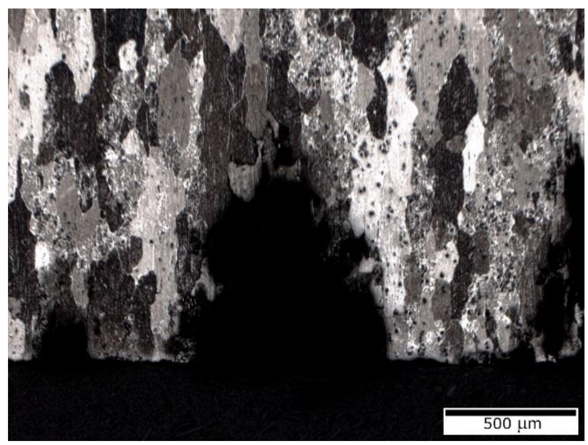
#23_unetched_m01_20x.jpg



#23_unetched_m02_50x.jpg



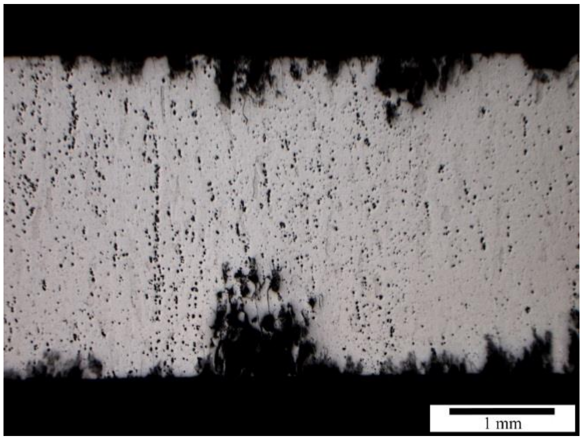
#23_etched_m03_20x.jpg



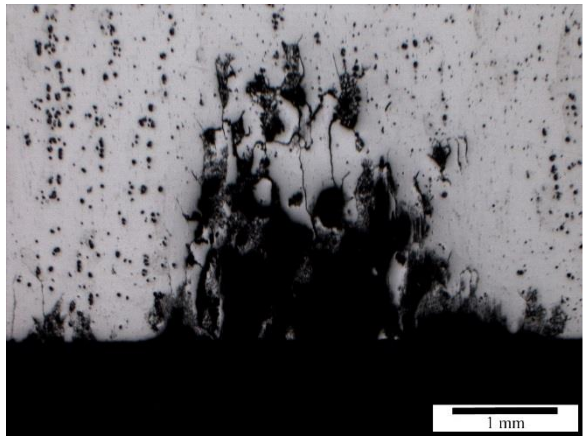
#23_etched_m04_50x.jpg

Coupon blank:	M7
Specimen No.:	23
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

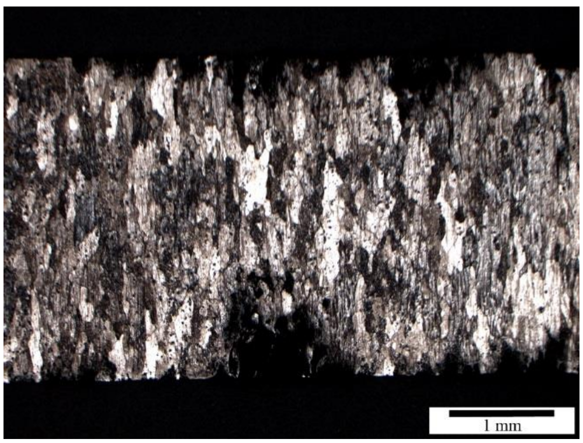
(a) 0% YS



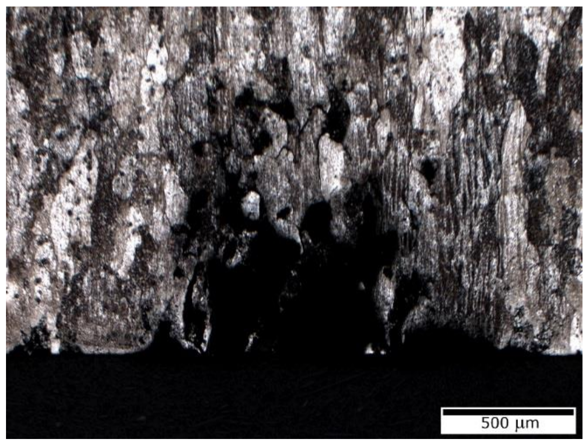
#26_unetched_m01_20x.jpg



#26_unetched_m02_50x.jpg



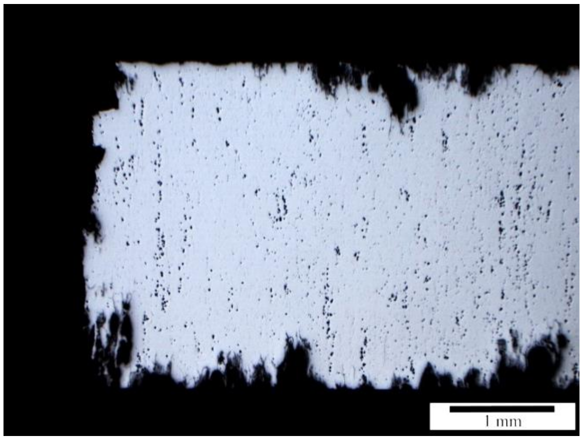
#26_etched_m03_20x.jpg



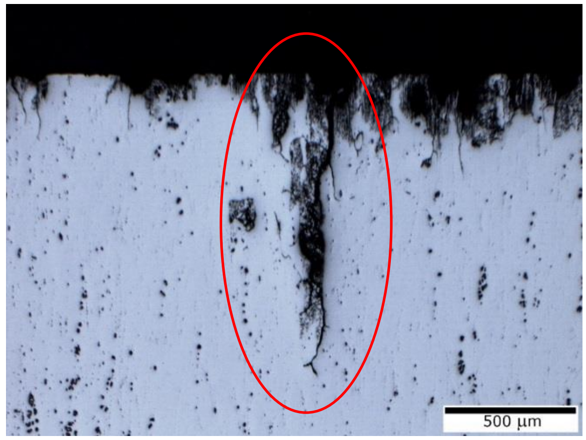
#26_etched_m04_50x.jpg

Coupon blank:	M7
Specimen No.:	26
Orientation:	ST
Applied stress (% YS):	50, based on M7 average ST YS
Applied stress (ksi):	21.60
Failed?:	No
SCC?:	No

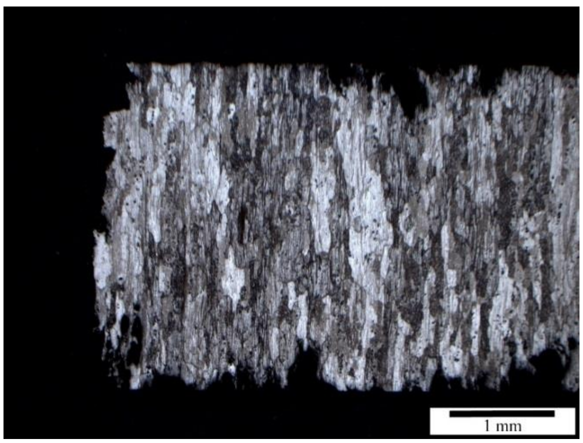
(b) 50% YS



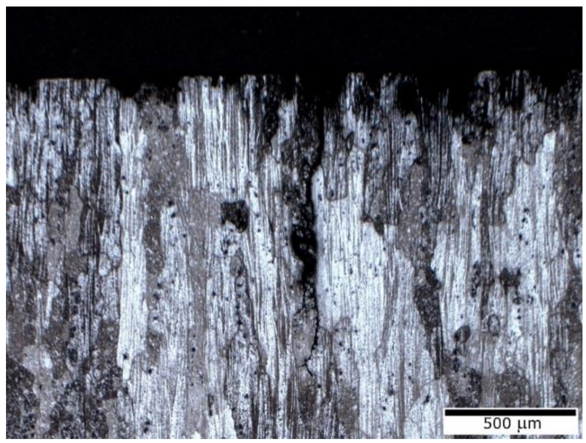
#29_unetched_m01_20x.jpg



#29_unetched_m02_50x.jpg



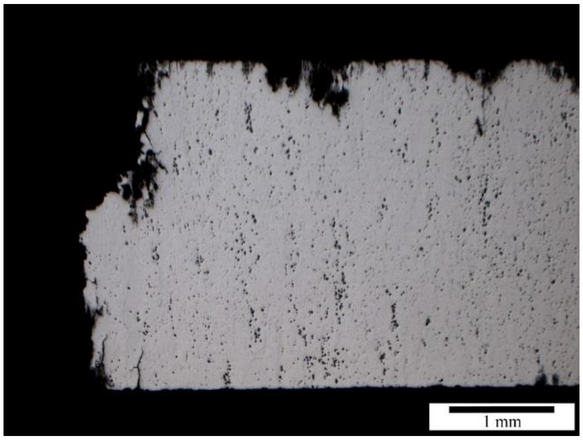
#29_etched_m03_20x.jpg



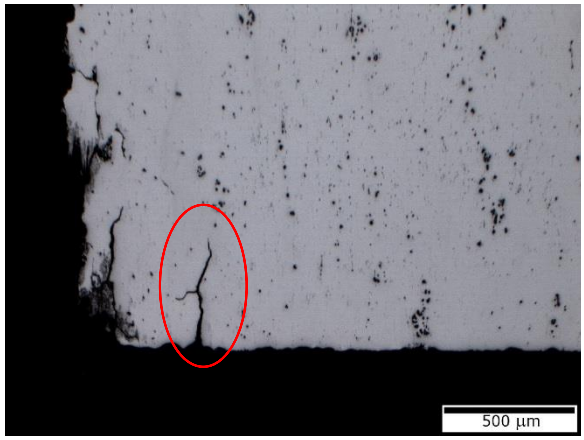
#29_etched_m04_50x.jpg

Coupon blank:	M7
Specimen No.:	29
Orientation:	ST
Applied stress (% YS):	75, based on M7 average ST YS
Applied stress (ksi):	32.4
Failed?:	Yes, 30 days
SCC?:	Yes; circled in red

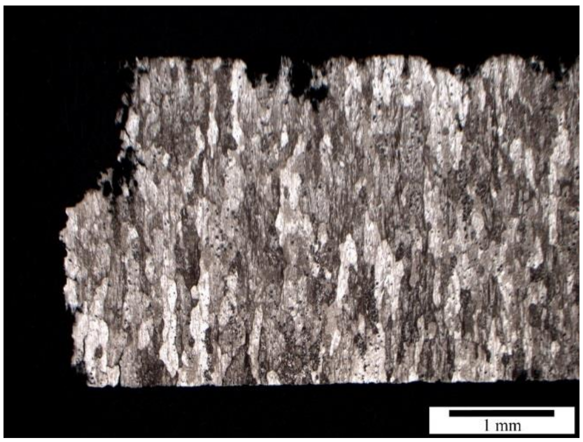
(c1) 75% YS



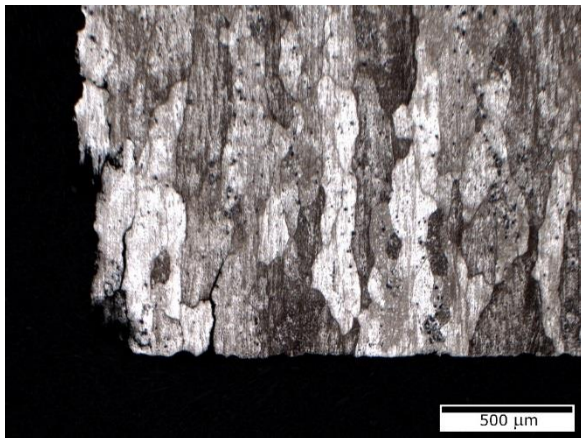
#30_unetched_m01_20x.jpg



#30_unetched_m02_50x.jpg



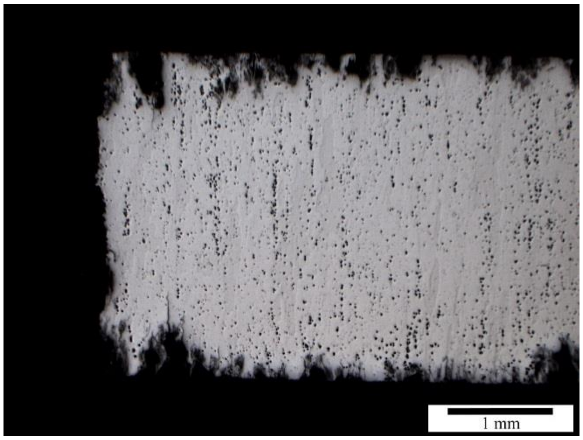
#30_etched_m03_20x.jpg



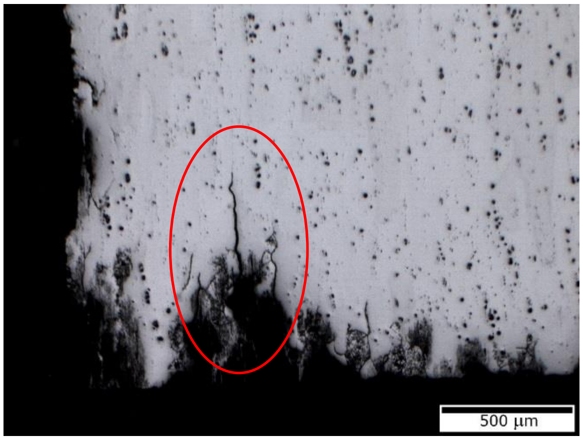
#30_etched_m04_50x.jpg

Coupon blank:	M7
Specimen No.:	30
Orientation:	ST
Applied stress (% YS):	75, based on M7 average ST YS
Applied stress (ksi):	32.4
Failed?:	Yes, 28 days
SCC?:	Yes; circled in red

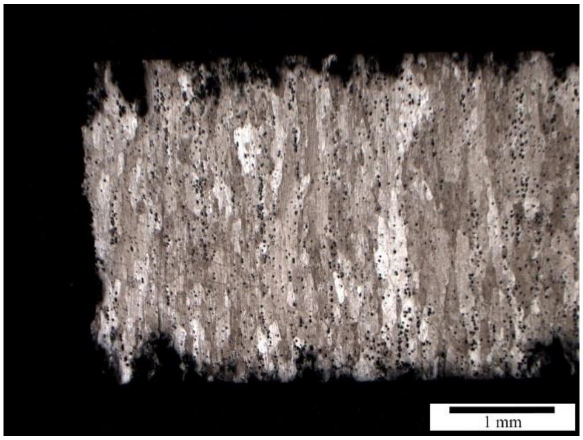
(c2) 75% YS



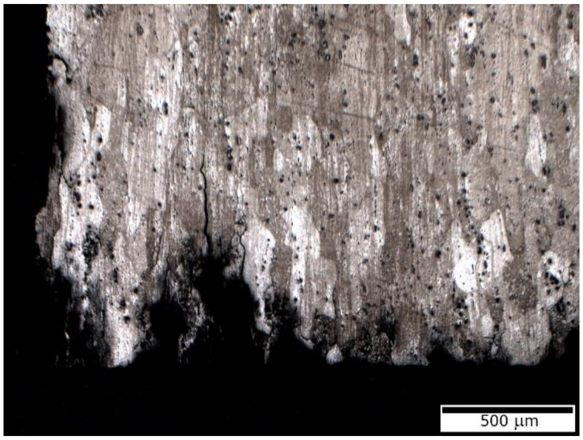
#31_unetched_m01_20x.jpg



#31_unetched_m02_50x.jpg



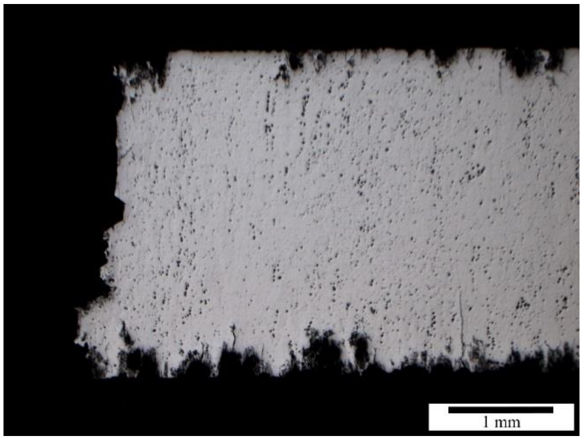
#31_etched_m03_20x.jpg



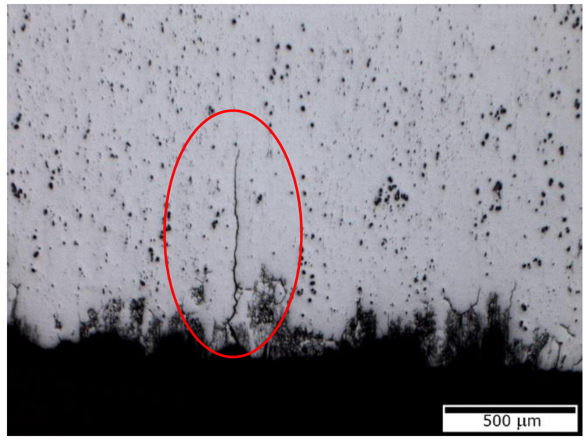
#31_etched_m04_50x.jpg

Coupon blank:	M7
Specimen No.:	31
Orientation:	ST
Applied stress (% YS):	75, based on M7 average ST YS
Applied stress (ksi):	32.4
Failed?:	Yes, 26 days
SCC?:	Yes; circled in red

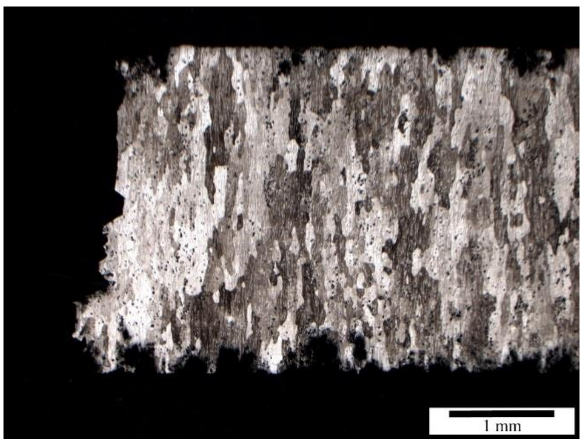
(c3) 75% YS



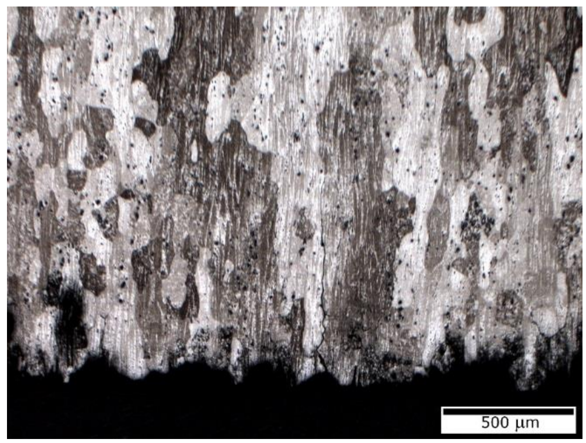
#33_unetched_m01_20x.jpg



#33_unetched_m02_50x.jpg



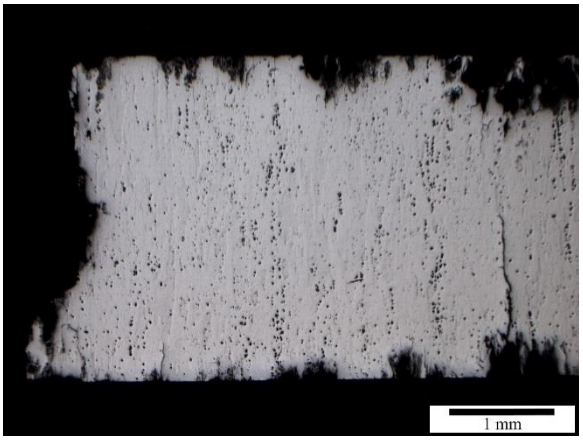
#33_etched_m03_20x.jpg



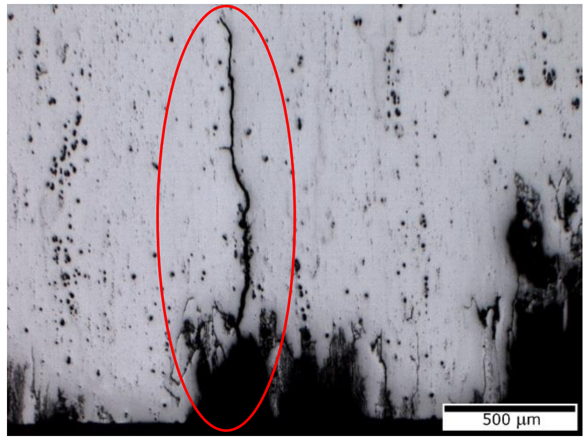
#33_etched_m04_50x.jpg

Coupon blank:	M7
Specimen No.:	33
Orientation:	ST
Applied stress (% YS):	90, based on M7 average ST YS
Applied stress (ksi):	38.88
Failed?:	Yes, 28 days
SCC?:	Yes; circled in red

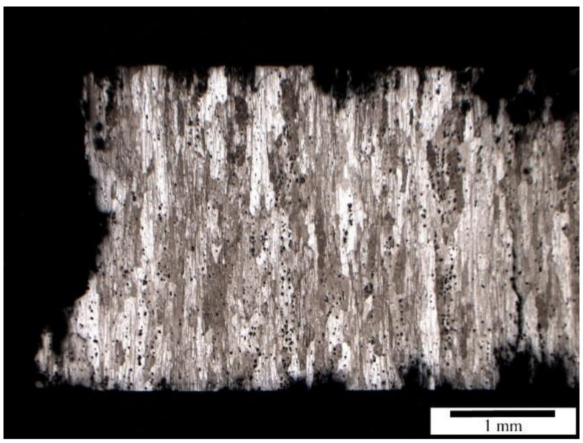
(d1) 90% YS



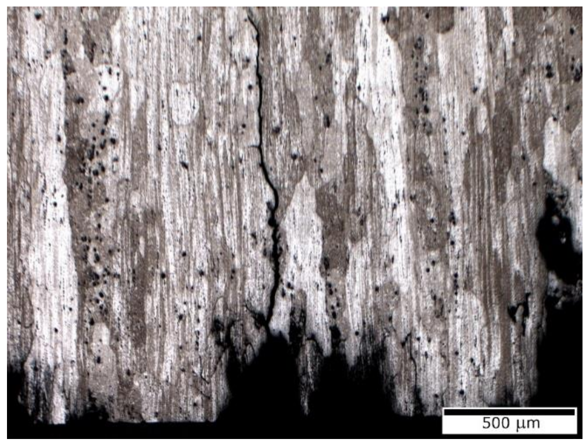
#34_unetched_m01_20x.jpg



#34_unetched_m02_50x.jpg



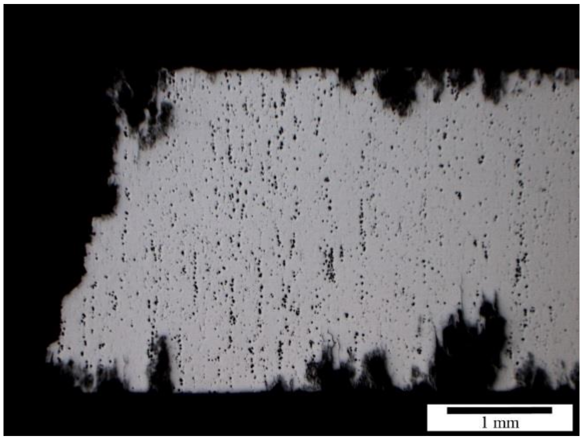
#34_etched_m03_20x.jpg



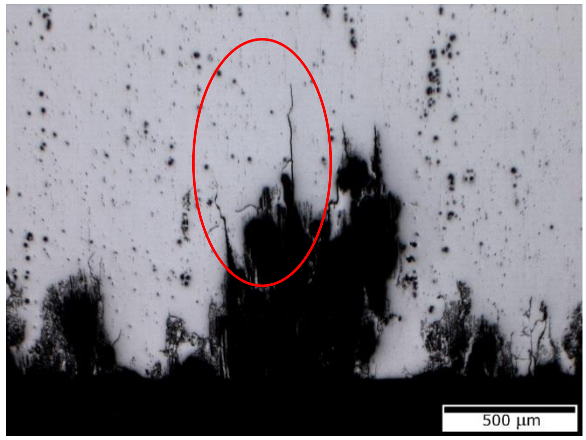
#34_etched_m04_50x.jpg

Coupon blank:	M7
Specimen No.:	34
Orientation:	ST
Applied stress (% YS):	90, based on M7 average ST YS
Applied stress (ksi):	38.88
Failed?:	Yes, 26 days
SCC?:	Yes; circled in red

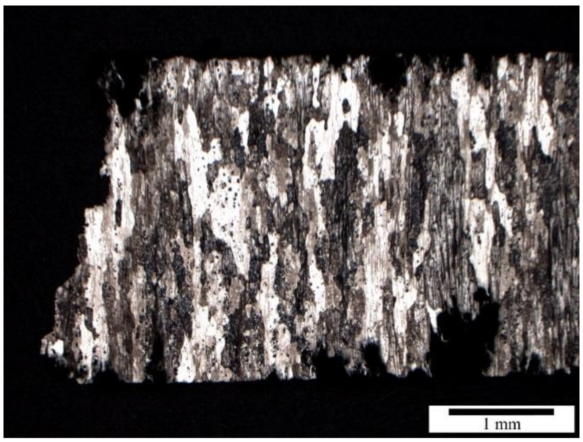
(d2) 90% YS



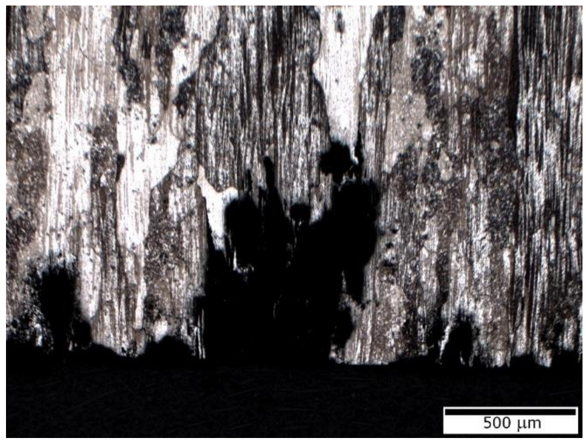
#35_unetched_m01_20x.jpg



#35_unetched_m02_50x.jpg



#35_etched_m03_20x.jpg

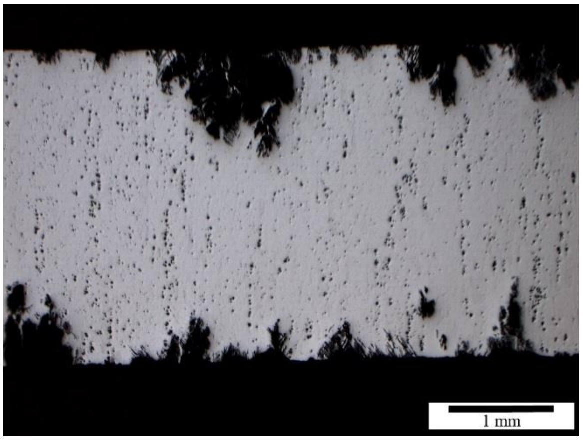


#35_etched_m04_50x.jpg

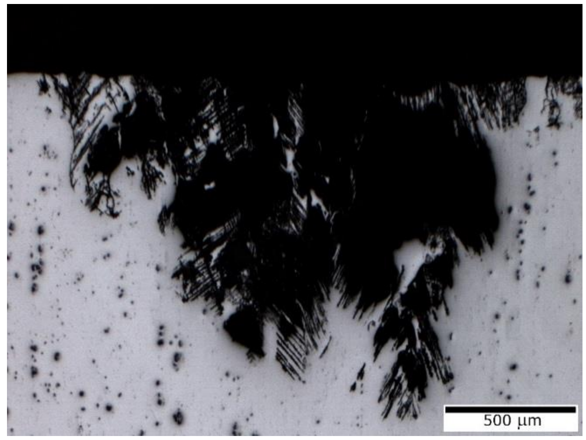
Coupon blank:	M7
Specimen No.:	35
Orientation:	ST
Applied stress (% YS):	90, based on M7 average ST YS
Applied stress (ksi):	38.88
Failed?:	Yes, 26 days
SCC?:	Yes; circled in red

(d3) 90% YS

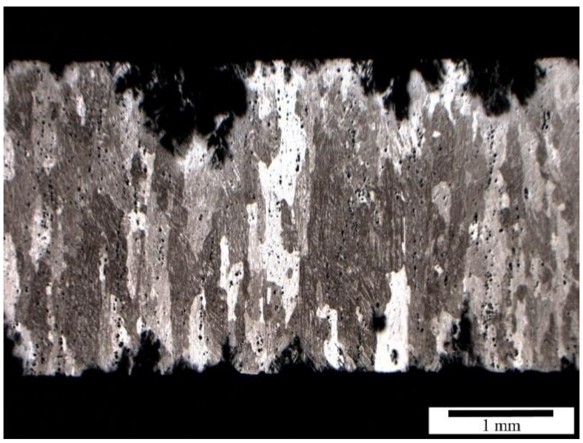
Figure B-1. ***Photomicrographs of SCC specimens from aft bulkhead coupon blank M7 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; (c1, c2, c3) 75% YS; and (d1, d2, d3) 90% YS.***



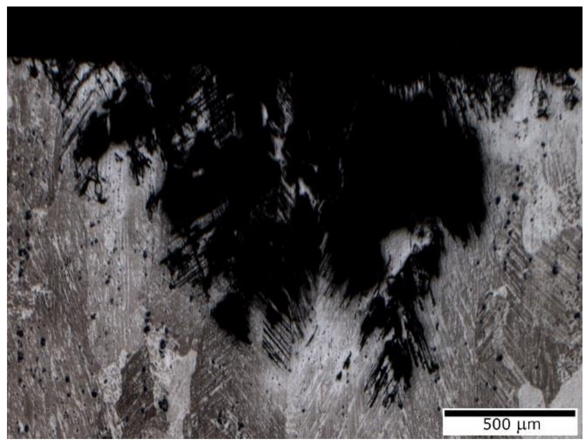
#65_unetched_m01_20x.jpg



#65_unetched_m02_50x.jpg



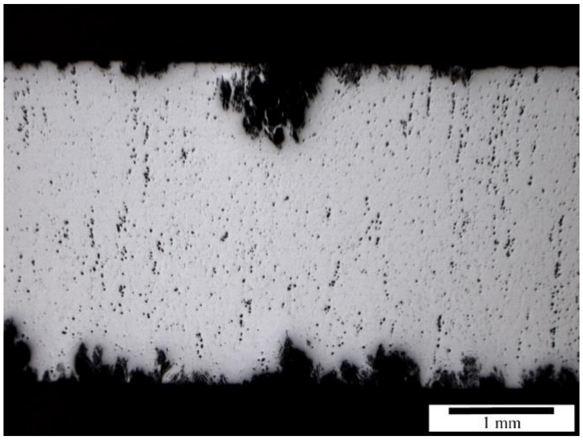
#65_etched_m03_20x.jpg



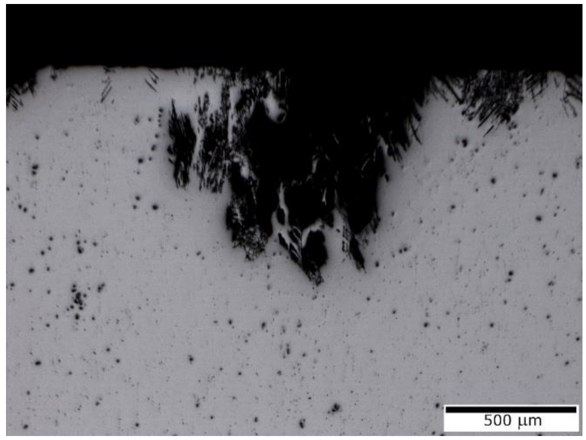
#65_etched_m04_50x.jpg

Coupon blank:	M8
Specimen No.:	65
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

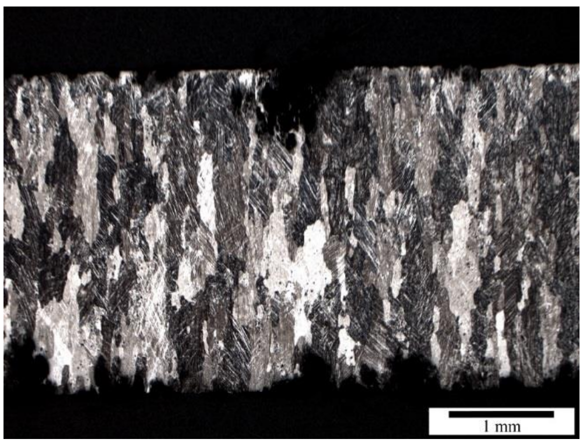
(a) 0% YS



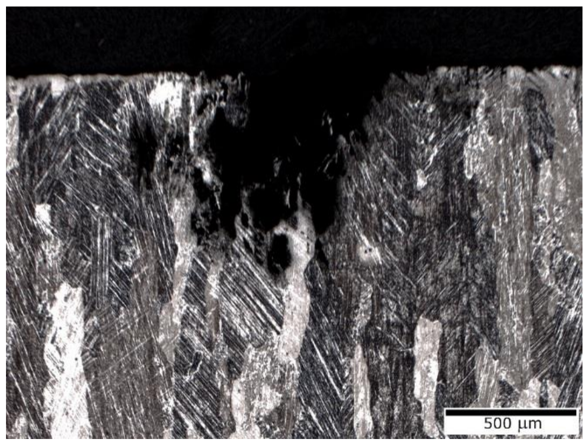
#68_unetched_m01_20x.jpg



#68_unetched_m02_50x.jpg



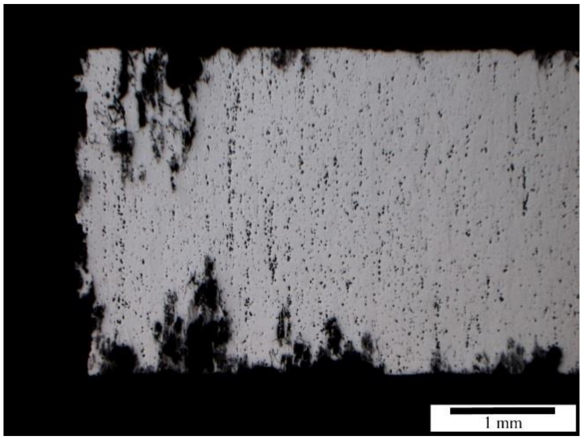
#68_etched_m03_20x.jpg



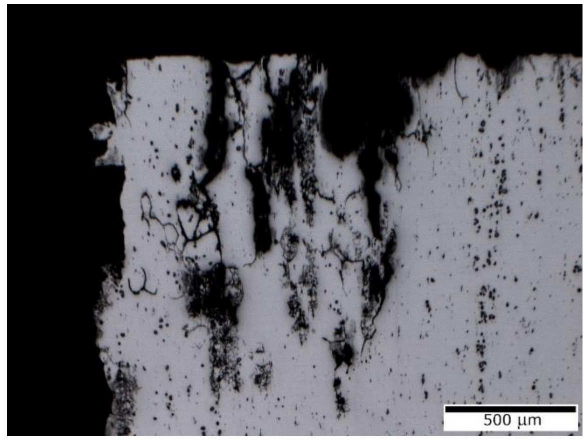
#68_etched_m04_50x.jpg

Coupon blank:	M8
Specimen No.:	68
Orientation:	ST
Applied stress (% YS):	50, based on M8 average ST YS
Applied stress (ksi):	21.87
Failed?:	No
SCC?:	No

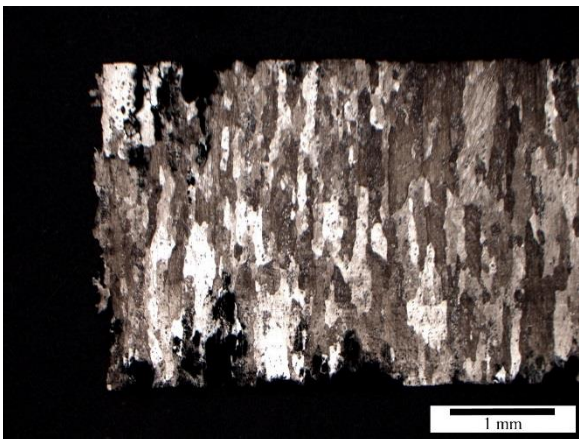
(b) 50% YS



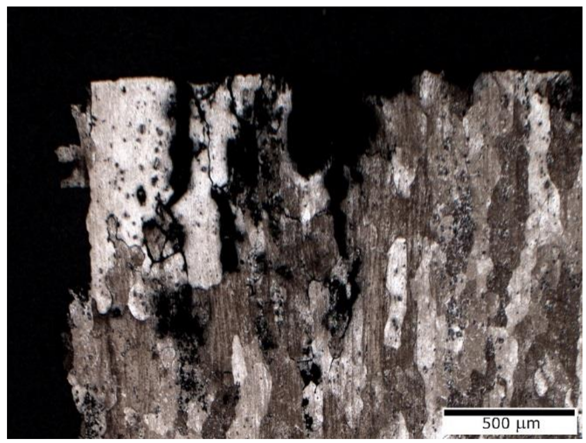
#71_unetched_m01_20x.jpg



#71_unetched_m02_50x.jpg



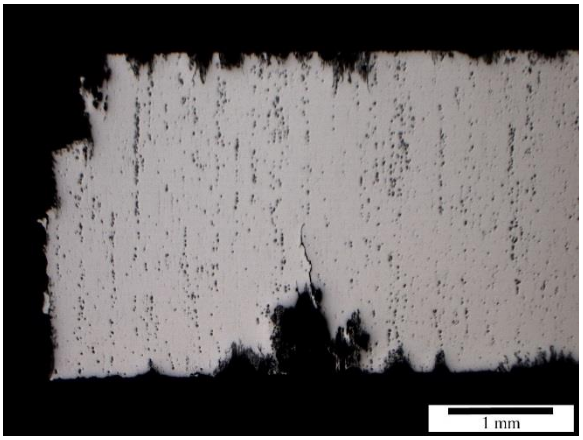
#71_etched_m03_20x.jpg



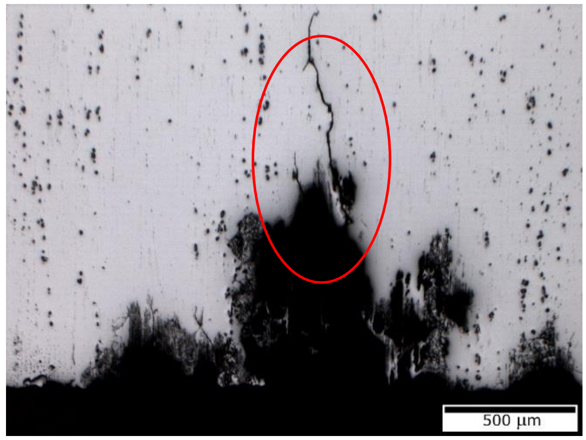
#71_etched_m04_50x.jpg

Coupon blank:	M8
Specimen No.:	71
Orientation:	ST
Applied stress (% YS):	75, based on M8 average ST YS
Applied stress (ksi):	32.80
Failed?:	Yes, 30 days
SCC?:	No

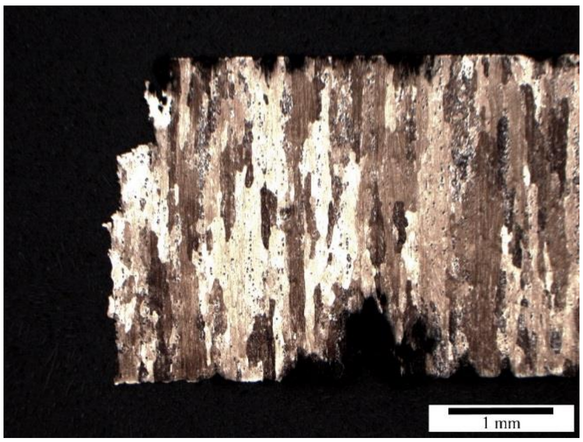
(c1) 75% YS



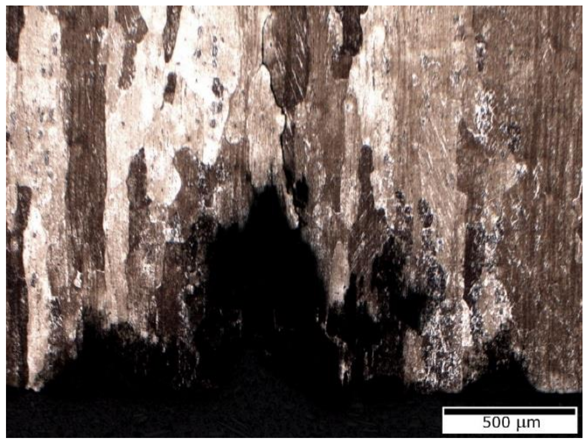
#73_unetched_m01_20x.jpg



#73_unetched_m02_50x.jpg



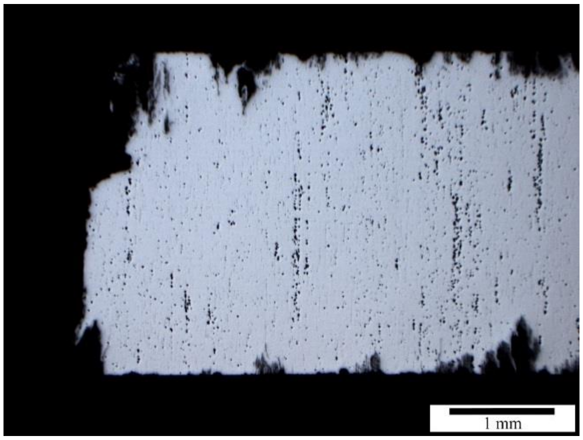
#73_etched_m03_20x.jpg



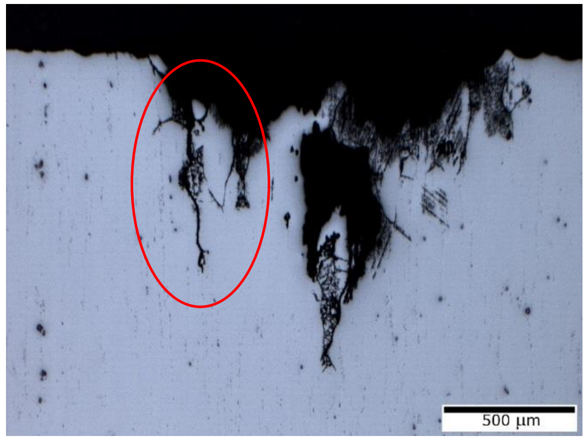
#73_etched_m04_50x.jpg

Coupon blank:	M8
Specimen No.:	73
Orientation:	ST
Applied stress (% YS):	75, based on M8 average ST YS
Applied stress (ksi):	32.80
Failed?:	Yes, 27 days
SCC?:	Yes; circled in red

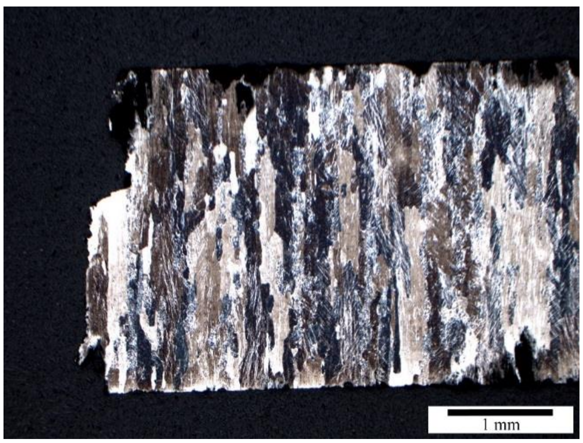
(c2) 75% YS



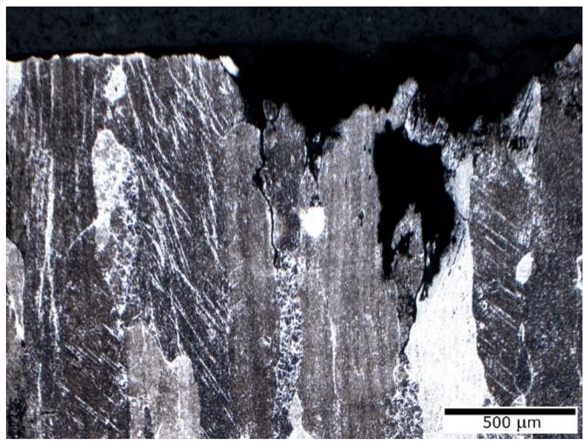
#75_unetched_m01_20x.jpg



#75_unetched_m02_50x.jpg



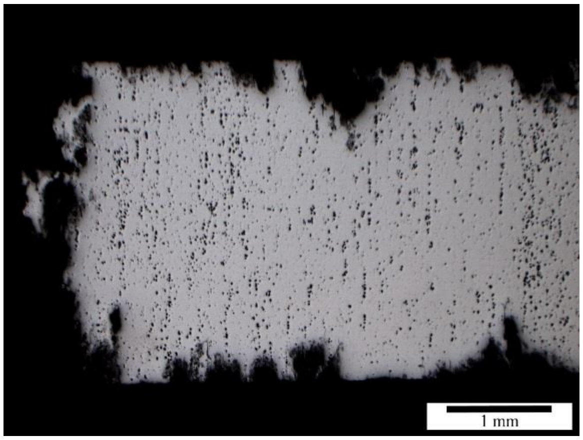
#75_etched_m03_20x.jpg



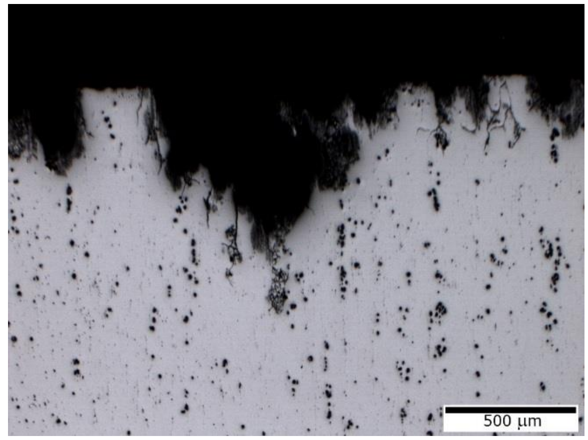
#75_etched_m04_50x.jpg

Coupon blank:	M8
Specimen No.:	75
Orientation:	ST
Applied stress (% YS):	90, based on M8 average ST YS
Applied stress (ksi):	39.36
Failed?:	Yes, 26 days
SCC?:	Yes; circled in red

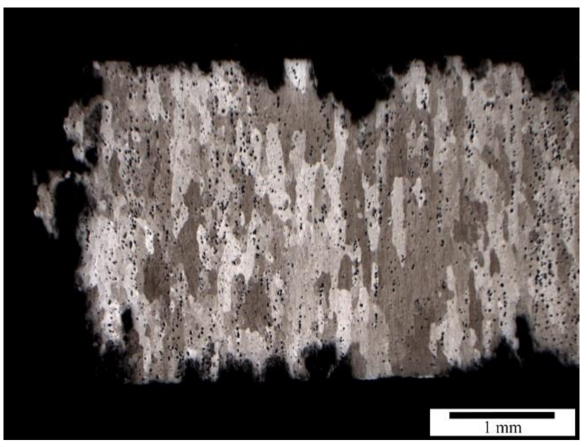
(d1) 90% YS



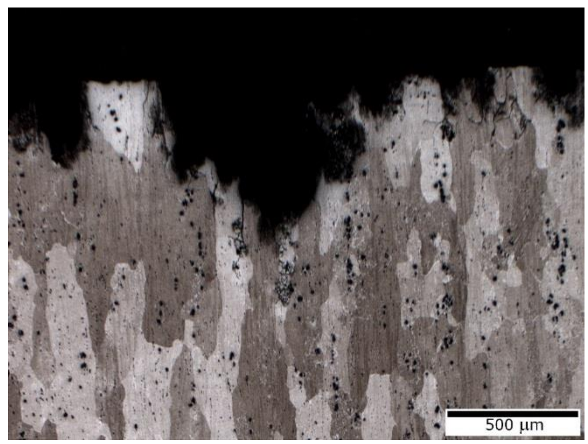
#76_unetched_m01_20x.jpg



#76_unetched_m02_50x.jpg



#76_etched_m03_20x.jpg

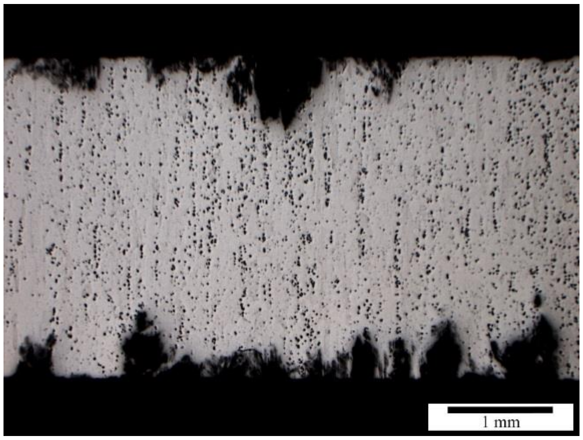


#76_etched_m04_50x.jpg

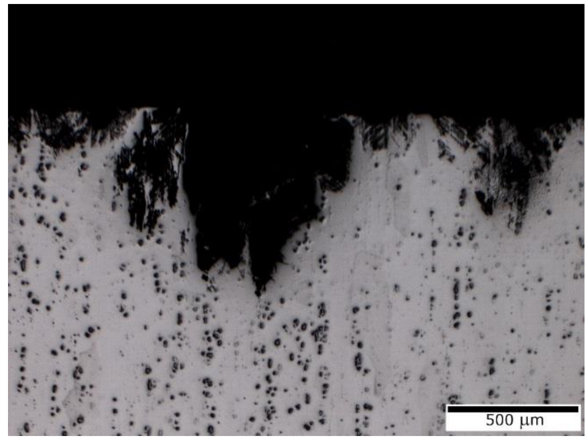
Coupon blank:	M8
Specimen No.:	76
Orientation:	ST
Applied stress (% YS):	90, based on M8 average ST YS
Applied stress (ksi):	39.36
Failed?:	Yes, 30 days
SCC?:	No

(d2) 90% YS

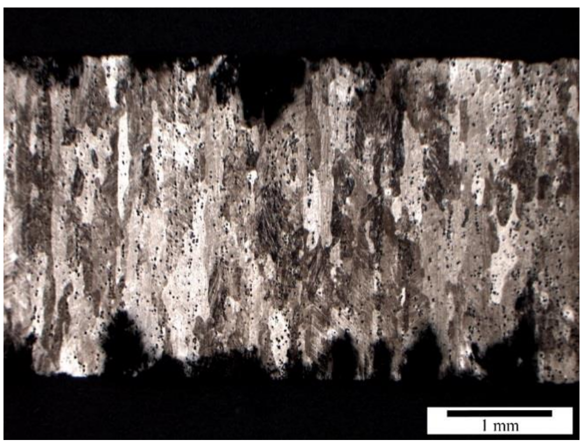
Figure B-2. Photomicrographs of SCC specimens from aft bulkhead coupon blank M8 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 50% YS; (c1, c2) 75% YS; and (d1, d2) 90% YS.



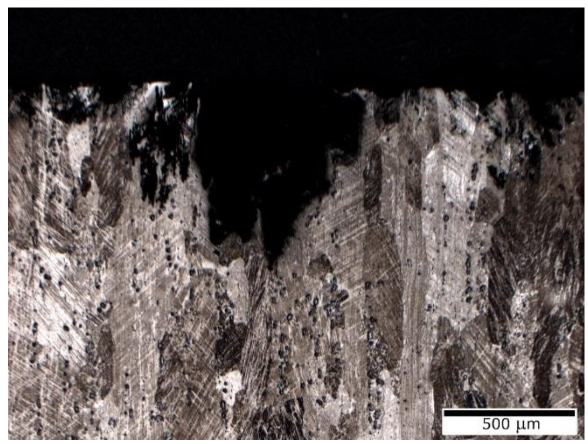
#107_unetched_m01_20x.jpg



#107_unetched_m02_50x.jpg



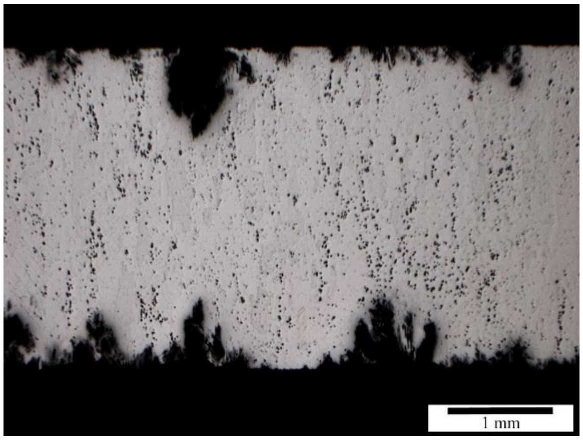
#107_etched_m03_20x.jpg



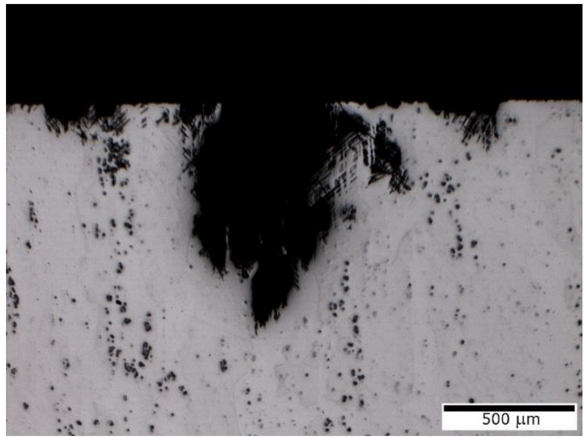
#107_etched_m04_50x.jpg

Coupon blank:	M9
Specimen No.:	107
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

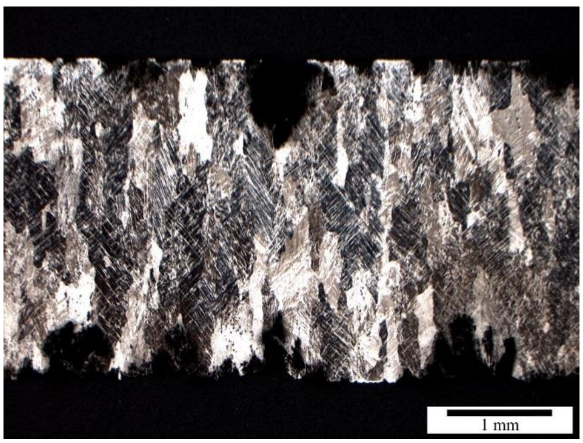
(a) 0% YS



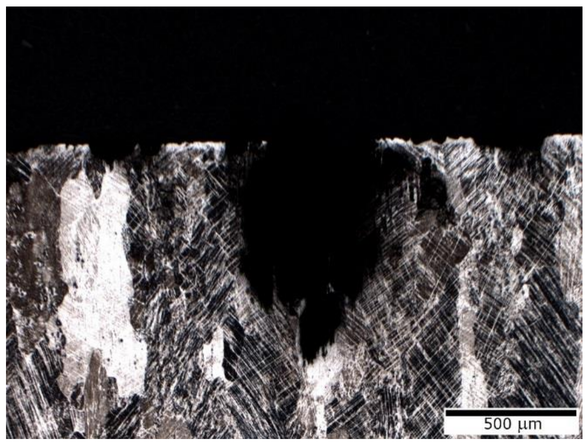
#113_unetched_m01_20x.jpg



#113_unetched_m02_50x.jpg



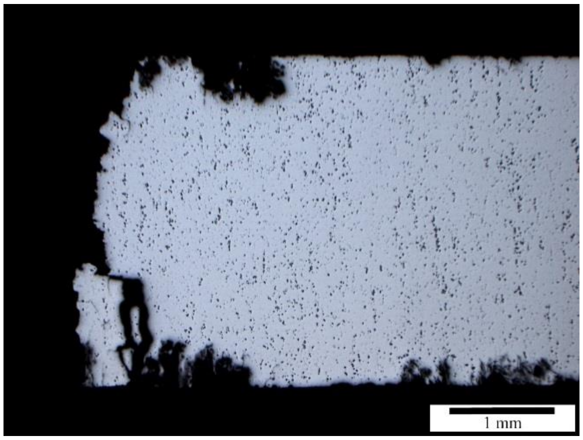
#113_etched_m03_20x.jpg



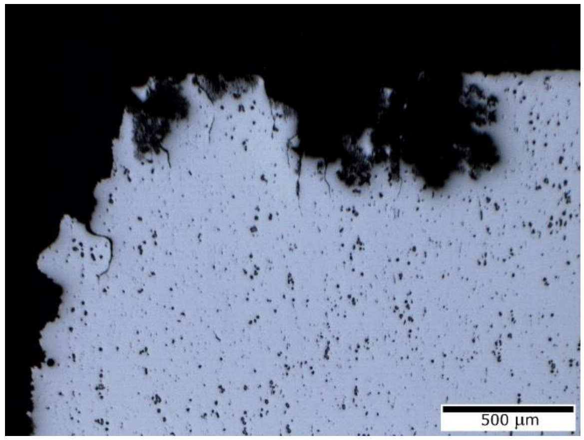
#113_etched_m04_50x.jpg

Coupon blank:	M9
Specimen No.:	113
Orientation:	ST
Applied stress (% YS):	75, based on M9 average ST YS
Applied stress (ksi):	33.25
Failed?:	No
SCC?:	No

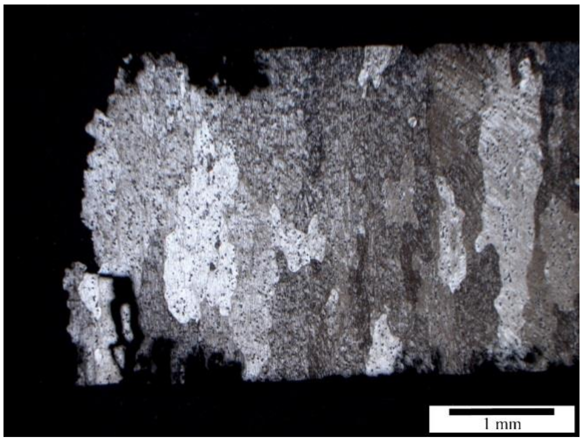
(b) 75% YS



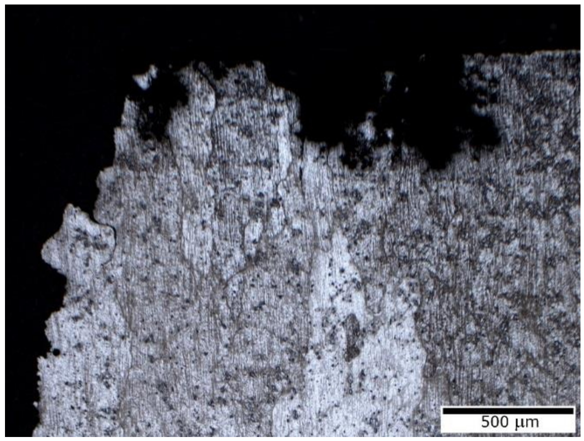
#117_unetched_m01_20x.jpg



#117_unetched_m02_50x.jpg



#117_etched_m03_20x.jpg

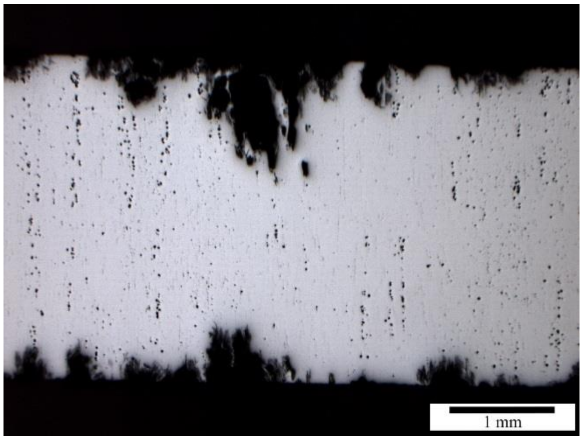


#117_etched_m04_50x.jpg

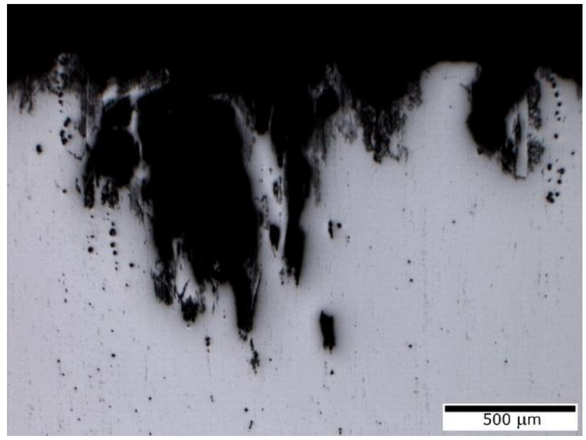
Coupon blank:	M9
Specimen No.:	117
Orientation:	ST
Applied stress (% YS):	90, based on M9 average ST YS
Applied stress (ksi):	39.9
Failed?:	Yes, 26 days
SCC?:	No

(c) 90% YS

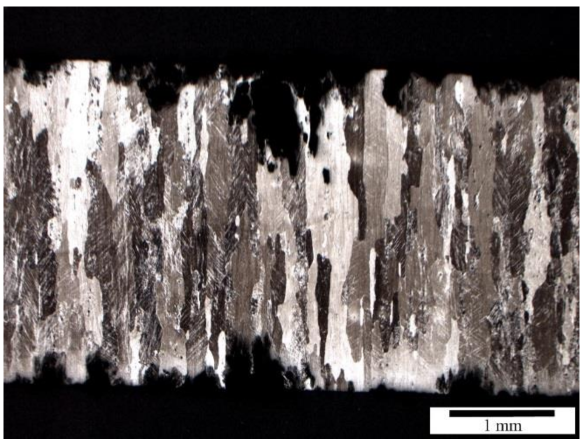
Figure B-3. Photomicrographs of SCC specimens from aft bulkhead coupon blank M9 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b) 75% YS; and (c) 90% YS.



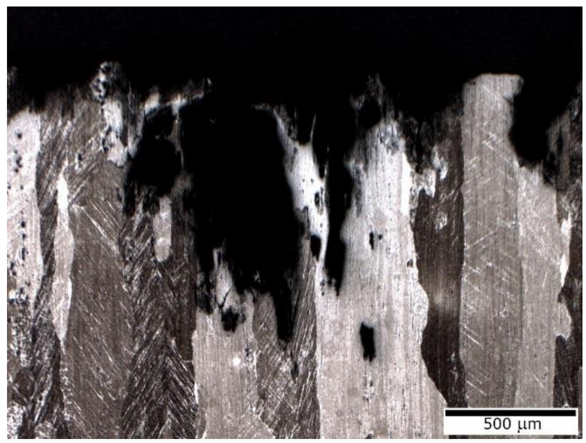
#149_unetched_m01_20x.jpg



#149_unetched_m02_50x.jpg



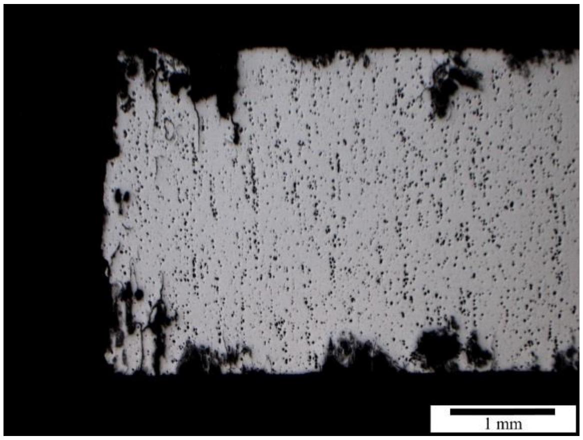
#149_etched_m03_20x.jpg



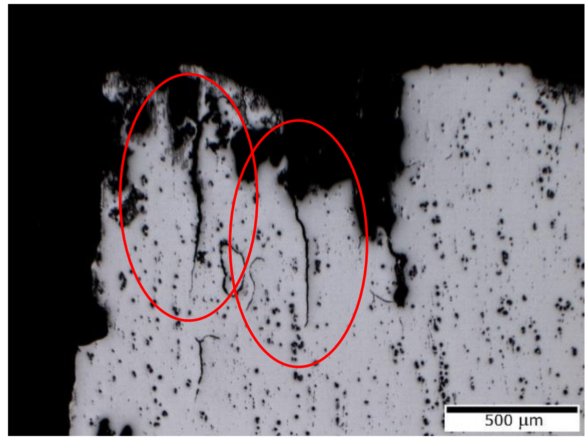
#149_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	149
Orientation:	ST
Applied stress (% YS):	0
Applied stress (ksi):	0
Failed?:	No
SCC?:	No

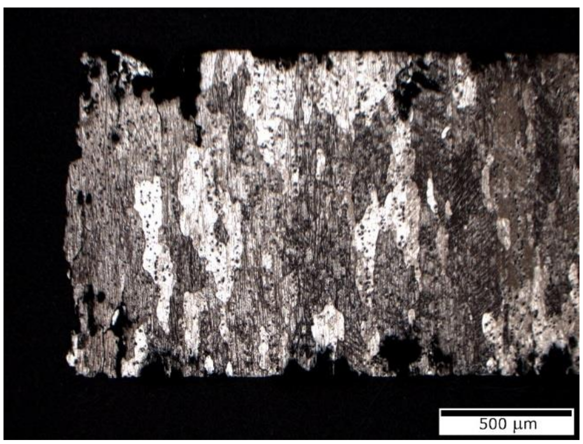
(a) 0% YS



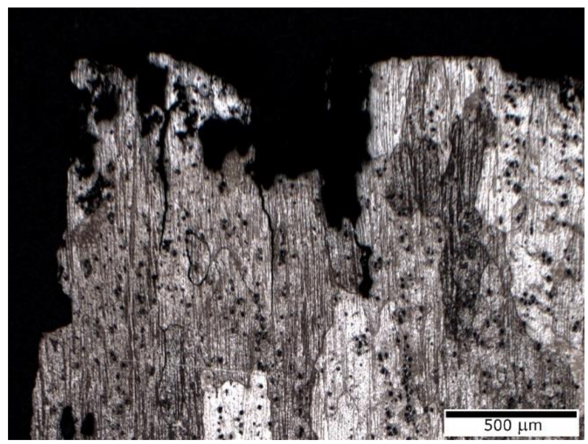
#152_unetched_m01_20x.jpg



#152_unetched_m02_50x.jpg



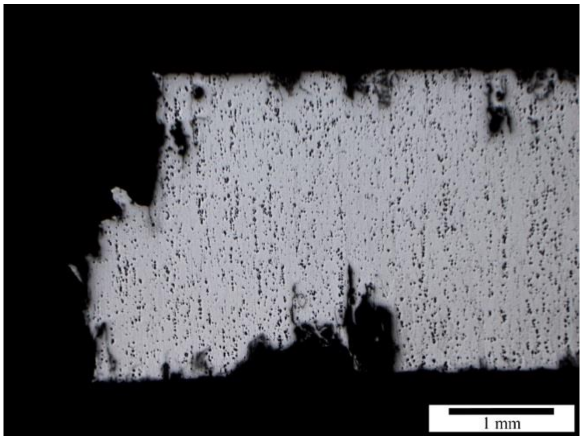
#152_etched_m03_20x.jpg



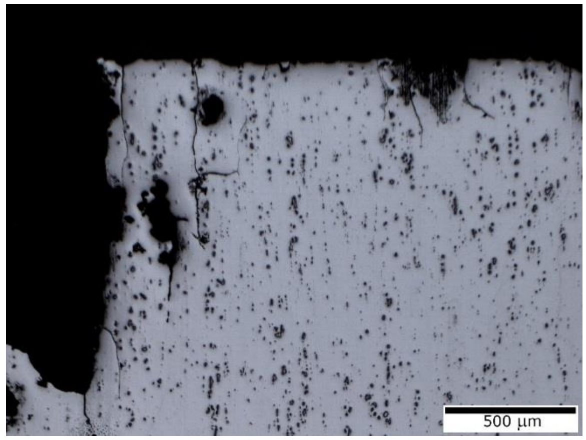
#152_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	152
Orientation:	ST
Applied stress (% YS):	50, based on M10 average ST YS
Applied stress (ksi):	22.21
Failed?:	Yes, 29 days
SCC?:	Yes; circled in red

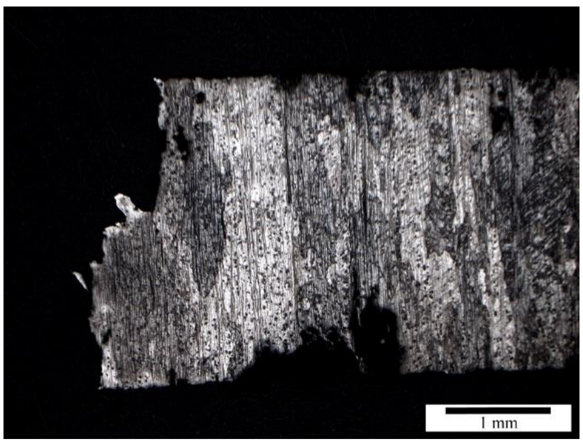
(b1) 50% YS



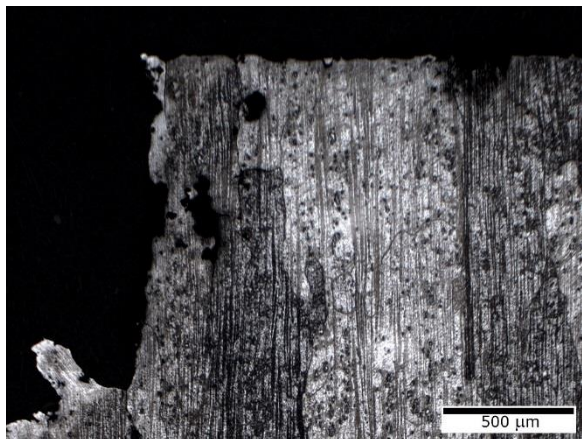
#153_unetched_m01_20x.jpg



#153_unetched_m02_50x.jpg



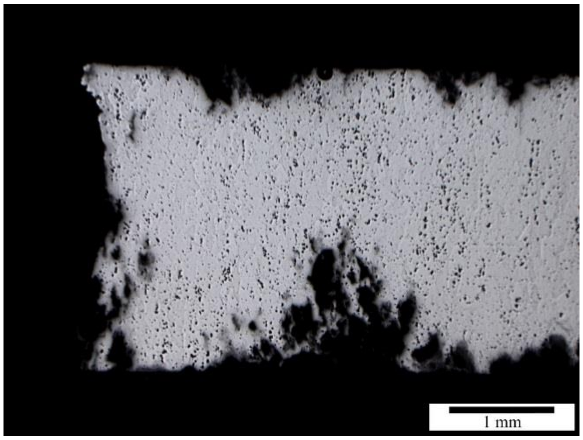
#153_etched_m03_20x.jpg



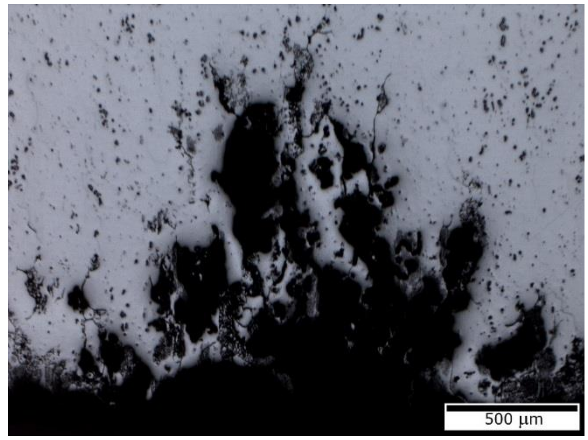
#153_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	153
Orientation:	ST
Applied stress (% YS):	50, based on M10 average ST YS
Applied stress (ksi):	22.21
Failed?:	No, residual strength test specimen
SCC?:	Not rated, tensile test may artificially open cracks

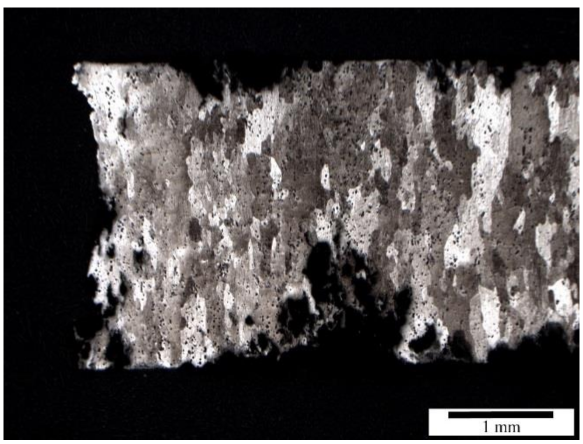
(b2) 50% YS



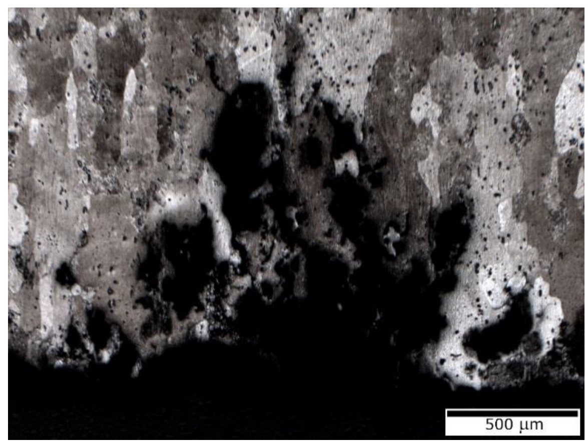
#154_unetched_m01_20x.jpg



#154_unetched_m02_50x.jpg



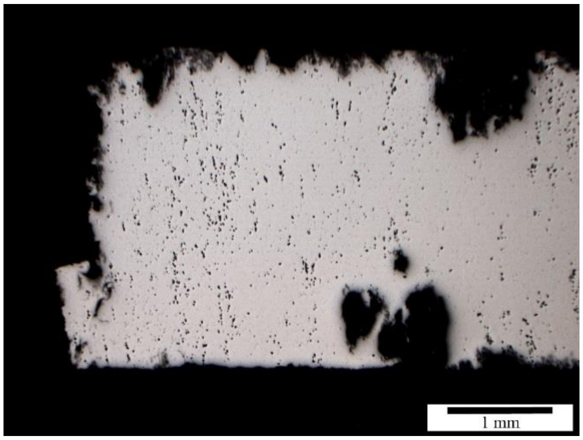
#154_etched_m03_20x.jpg



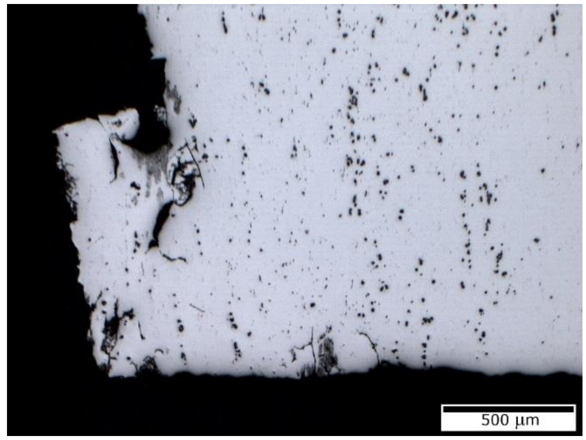
#154_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	154
Orientation:	ST
Applied stress (% YS):	50, based on M10 average ST YS
Applied stress (ksi):	22.21
Failed?:	No, residual strength test specimen
SCC?:	Not rated, tensile test may artificially open cracks

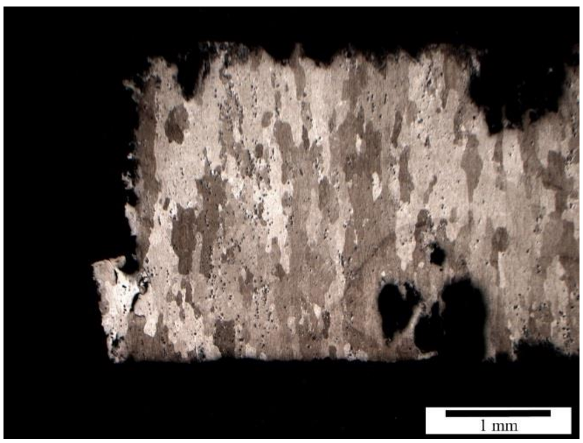
(b3) 50% YS



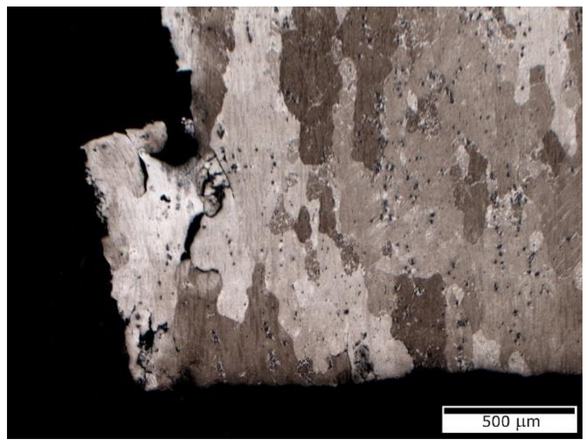
#156_unetched_m01_20x.jpg



#156_unetched_m02_50x.jpg



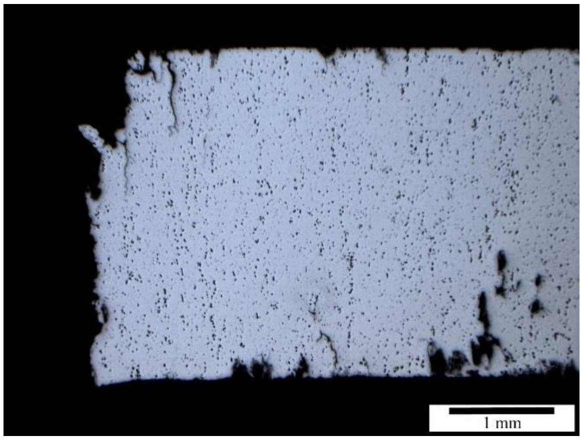
#156_etched_m03_20x.jpg



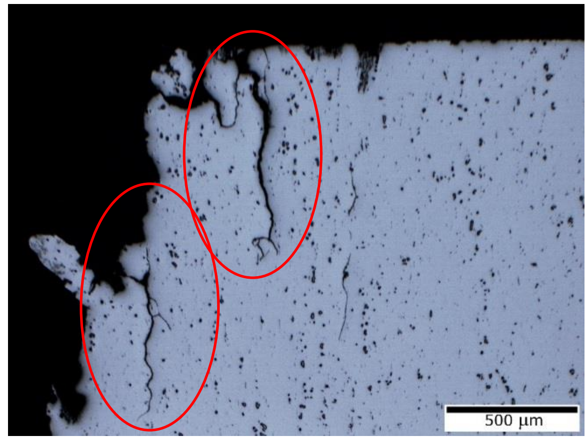
#156_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	156
Orientation:	ST
Applied stress (% YS):	75, based on M10 average ST YS
Applied stress (ksi):	33.31
Failed?:	Yes, 30 days
SCC?:	No

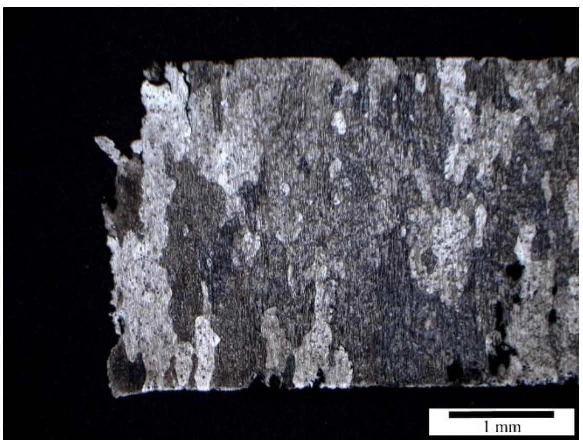
(c1) 75% YS



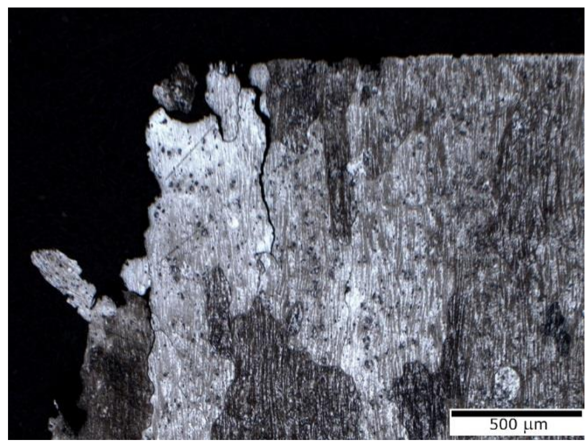
#157_unetched_m01_20x.jpg



#157_unetched_m02_50x.jpg



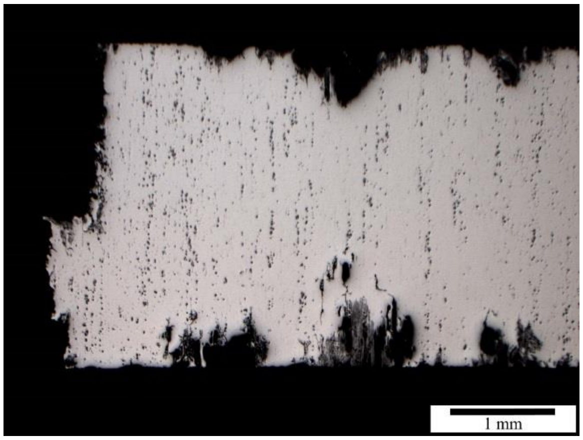
#157_etched_m03_20x.jpg



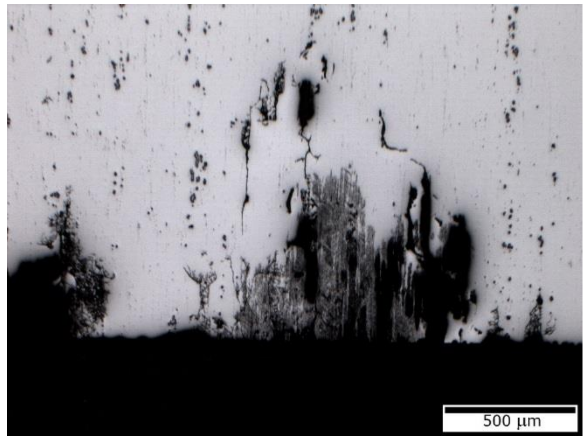
#157_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	157
Orientation:	ST
Applied stress (% YS):	75, based on M10 average ST YS
Applied stress (ksi):	33.31
Failed?:	Yes, 26 days
SCC?:	Yes; circled in red

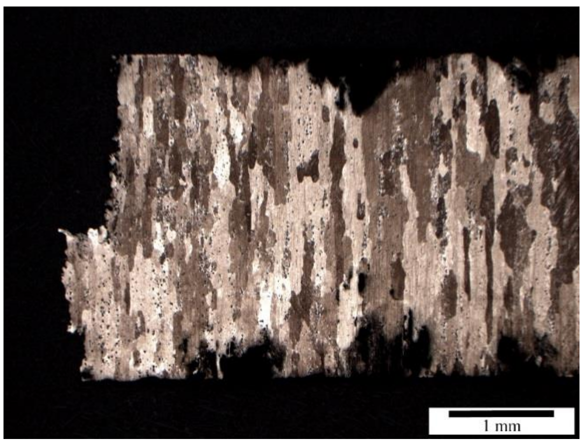
(c2) 75% YS



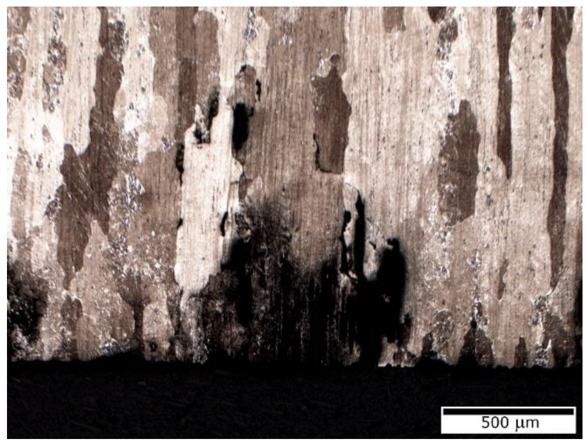
#159_unetched_m01_20x.jpg



#159_unetched_m02_50x.jpg



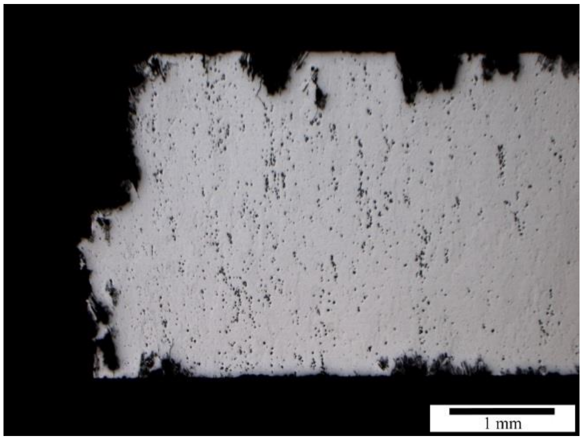
#159_etched_m03_20x.jpg



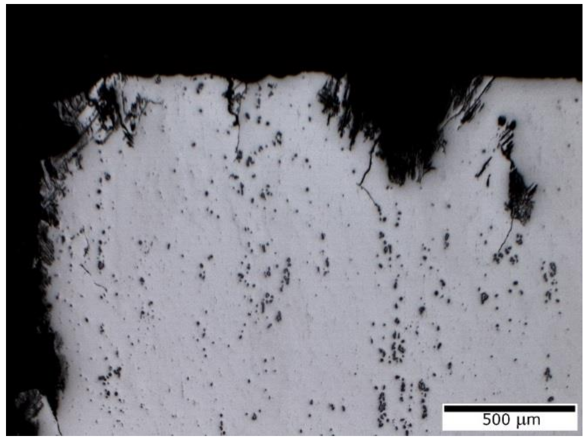
#159_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	159
Orientation:	ST
Applied stress (% YS):	90, based on M10 average ST YS
Applied stress (ksi):	39.37
Failed?:	Yes, 30 days
SCC?:	No

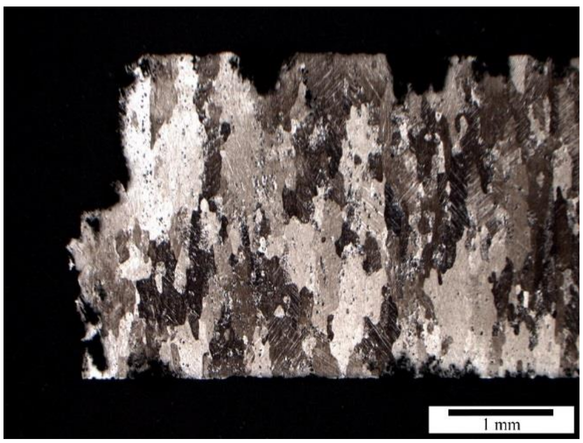
(d1) 90% YS



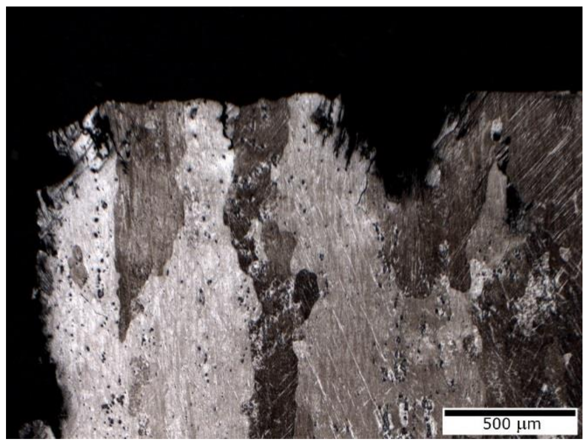
#160_unetched_m01_20x.jpg



#160_unetched_m02_50x.jpg



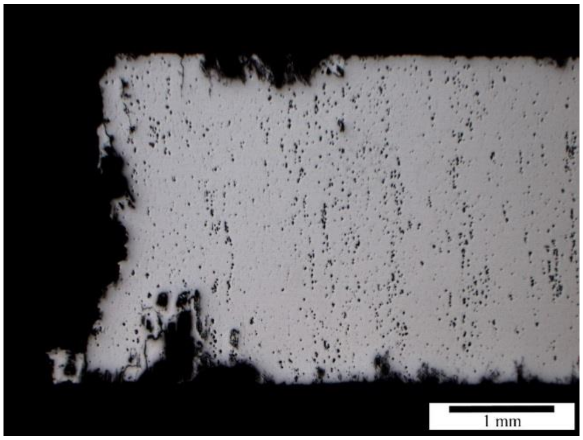
#160_etched_m03_20x.jpg



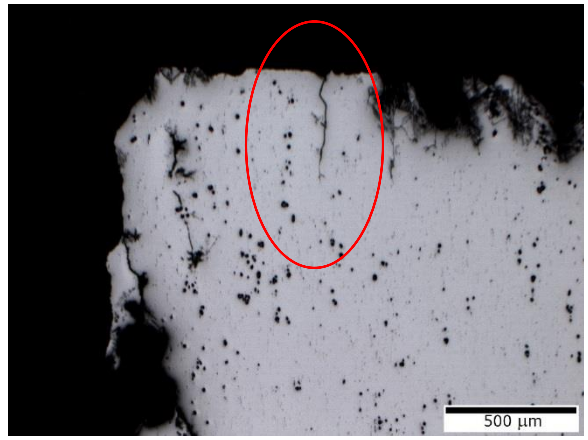
#160_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	160
Orientation:	ST
Applied stress (% YS):	90, based on M10 average ST YS
Applied stress (ksi):	39.37
Failed?:	Yes, 29 days
SCC?:	No

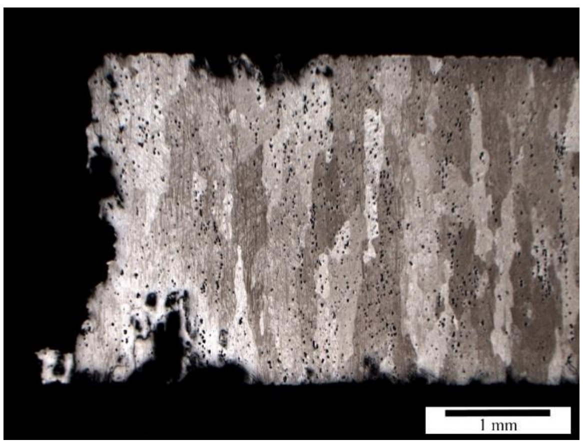
(d2) 90% YS



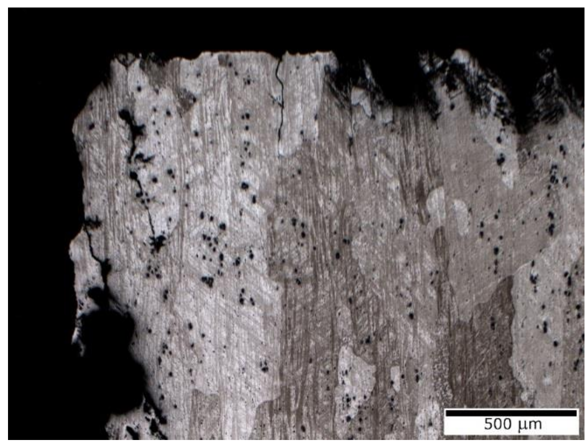
#161_unetched_m01_20x.jpg



#161_unetched_m02_50x.jpg



#161_etched_m03_20x.jpg



#161_etched_m04_50x.jpg

Coupon blank:	M10
Specimen No.:	161
Orientation:	ST
Applied stress (% YS):	90, based on M10 average ST YS
Applied stress (ksi):	39.37
Failed?:	Yes, 29 days
SCC?:	Yes; circled in red

(d3) 90% YS

Figure B-4. Photomicrographs of SCC specimens from aft bulkhead coupon blank M10 following 30-day 3.5% NaCl alternate immersion exposure at applied stress levels of (a) 0% YS; (b1, b2, b3) 50% YS; (c1, c2) 75% YS; and (d1, d2, d3) 90% YS.

11.3 Appendix C: Summary of the Supplemental SCC Test Results following 30-day 3.5% NaCl Alternate Immersion Exposure

Table C-1. Supplemental SCC test results for spin formed Al 2219-T62 aft bulkhead, CPST dome and wrought plate materials following 30-day 3.5% NaCl alternate immersion exposure.

Coupon Blank	Specimen No.	Orientation	Applied Stress Level ksi	Applied Stress Level % Measured ST YS	Applied Stress Level % MMPDS LT YS	Days to Failure	Post SCC Test Evaluation	Residual Tensile Strength ksi (1)	Percent Tensile Strength Retained (2)	Residual Strength Ratio (3)	SCC? Metallo-graphic Examination	Photo-micrograph Figure No.
	M10-1	ST	0	0	0	No failure	Tensile	38.19	64	----	----	----
	M10-2	ST	0	0	0	No failure	Tensile	23.79	40	----	----	----
	M10-3	ST	0	0	0	No failure	Micro	----	----	----	No	5 (a)
	M10-13	ST	18.00	40.5	50	No failure	Tensile	34.34	58	1.11	----	----
	M10-14	ST	18.00	40.5	50	No failure	Tensile	32.32	55	1.04	----	----
	M10-15	ST	18.00	40.5	50	No failure	Micro	32.32	----	----	Yes	5 (c)
	M10-4	ST	22.20	50.0	62	No failure	Tensile	35.48	60	1.14	----	----
M10	M10-5	ST	22.20	50.0	62	No failure	Tensile	33.29	56	1.07	----	----
	M10-6	ST	22.20	50.0	62	No failure	Micro	----	----	----	Yes	5 (b)
	M10-17	ST	27.00	60.8	75	No failure	Tensile	33.73	57	1.09	----	----
	M10-18	ST	27.00	60.8	75	No failure	Tensile	38.03	64	1.23	----	----
	M10-16	ST	27.00	60.8	75	No failure	Micro	----	----	----	Yes	5 (e)
	M10-7	ST	33.30	75.0	93	No failure	Tensile	31.80	54	1.03	----	----
	M10-8	ST	33.30	75.0	93	No failure	Tensile	36.71	62	1.18	----	----
	M10-9	ST	33.30	75.0	93	No failure	Micro	----	----	----	Yes	5 (d)
	J1-7	ST	0	0	0	No failure	Tensile	36.59	66	----	----	----
	J1-9	ST	0	0	0	No failure	Tensile	27.55	50	----	----	----
	J1-8	ST	0	0	0	No failure	Micro	----	----	----	No	6 (a)
	J1-4	ST	18.00	43.0	50	No failure	Tensile	28.11	51	0.88	----	----
J1	J1-5	ST	18.00	43.0	50	No failure	Tensile	33.00	60	1.03	----	----
	J1-6	ST	18.00	43.0	50	No failure	Micro	----	----	----	No	6 (b)
	J1-1	ST	27.00	64.5	75	No failure	Tensile	29.58	54	0.92	----	----
	J1-3	ST	27.00	64.5	75	No failure	Tensile	32.92	60	1.03	----	----
	J1-2	ST	27.00	64.5	75	No failure	Micro	----	----	----	Yes	6 (c)
	J2-7	ST	0	0	0	No failure	Tensile	29.67	52	----	----	----
	J2-9	ST	0	0	0	No failure	Tensile	34.07	60	----	----	----
	J2-8	ST	0	0	0	No failure	Micro	----	----	----	No	7 (a)
	J2-4	ST	18.00	41.8	50	No failure	Tensile	37.08	65	1.16	----	----
J2	J2-6	ST	18.00	41.8	50	No failure	Tensile	30.97	54	0.97	----	----
	J2-5	ST	18.00	41.8	50	No failure	Micro	----	----	----	Yes	7 (b)
	J2-1	ST	27.00	62.6	75	No failure	Tensile	31.37	55	0.98	----	----
	J2-3	ST	27.00	62.6	75	No failure	Tensile	33.17	58	1.04	----	----
	J2-2	ST	27.00	62.6	75	No failure	Micro	----	----	----	No	7 (c)
	J3-7	ST	0	0	0	No failure	Tensile	36.92	64	----	----	----
	J3-9	ST	0	0	0	No failure	Tensile	40.34	69	----	----	----
	J3-8	ST	0	0	0	No failure	Micro	----	----	----	No	8 (a)
	J3-4	ST	18.00	41.1	50	No failure	Tensile	37.65	65	0.97	----	----
J3	J3-6	ST	18.00	41.1	50	No failure	Tensile	39.93	69	1.03	----	----
	J3-5	ST	18.00	41.1	50	No failure	Micro	----	----	----	No	8 (b)
	J3-1	ST	27.00	61.6	75	No failure	Tensile	32.68	57	0.85	----	----
	J3-2	ST	27.00	61.6	75	No failure	Tensile	41.97	73	1.09	----	----
	J3-3	ST	27.00	61.6	75	No failure	Micro	----	----	----	No	8 (c)

Table C-1. Supplemental SCC test results for spin formed Al 2219-T62 aft bulkhead, CPST dome and wrought plate materials following 30-day 3.5% NaCl alternate immersion exposure (continued).

Coupon Blank	Specimen No.	Orientation	Applied Stress Level ksi	Applied Stress Level % Measured ST YS	Applied Stress Level % MMPDS LT YS	Days to Failure	Post SCC Test Evaluation	Residual Tensile Strength ksi(1)	Percent Tensile Strength Retained(2)	Residual Strength Ratio(3)	SCC? Metallo-graphic Examination	Photo-micrograph Figure No.
Standard Plate	WQ-1	ST	0	0	0	No failure	Tensile	28.53	46	----	----	----
	WQ-2	ST	0	0	0	No failure	Tensile	28.36	46	----	----	----
	WQ-3	ST	0	0	0	No failure	Micro	----	----	----	No	9 (a)
	WQ-4	ST	18.00	41.4	50	No failure	Tensile	34.96	57	1.23	----	----
	WQ-5	ST	18.00	41.4	50	No failure	Tensile	33.99	55	1.19	----	----
	WQ-6	ST	18.00	41.4	50	No failure	Micro	----	----	----	No	9 (b)
	WQ-7	ST	27.00	62.1	75	No failure	Tensile	27.84	45	0.98	----	----
	WQ-8	ST	27.00	62.1	75	No failure	Tensile	28.63	46	1.01	----	----
	WQ-9	ST	27.00	62.1	75	No failure	Micro	----	----	----	No	9 (c)
Modified Plate	GQ-2	ST	0	0	0	No failure	Tensile	43.63	74	----	----	----
	GQ-3	ST	0	0	0	No failure	Tensile	34.5	58	----	----	----
	GQ-1	ST	0	0	0	No failure	Micro	----	----	----	No	10 (a)
	GQ-5	ST	18.00	48.4	50	No failure	Tensile	33.99	57	0.87	----	----
	GQ-6	ST	18.00	48.4	50	No failure	Tensile	30.65	52	0.78	----	----
	GQ-4	ST	18.00	48.4	50	No failure	Micro	----	----	----	Yes	10 (b)
	GQ-8	ST	27.00	72.6	75	No failure	Tensile	36.71	62	0.94	----	----
	GQ-9	ST	27.00	72.6	75	No failure	Tensile	37.15	63	0.95	----	----
	GQ-7	ST	27.00	72.6	75	No failure	Micro	----	----	----	No	10 (c)
CPST Dome Pole	CP-P1	ST	0	0	0	No failure	Tensile	33.36	59	----	----	----
	CP-P3	ST	0	0	0	No failure	Tensile	32.66	58	----	----	----
	CP-P2	ST	0	0	0	No failure	Micro	----	----	----	No	11 (a)
	CP-P4	ST	18.00	44.8	50	No failure	Tensile	27.93	50	0.85	----	----
	CP-P5	ST	18.00	44.8	50	No failure	Tensile	19.24	34	0.58 (4)	----	----
	CP-P6	ST	18.00	44.8	50	No failure	Micro	----	----	----	No	11 (b)
	CP-P7	ST	27.00	67.2	75	No failure	Tensile	26.26	47	0.8	----	----
	CP-P8	ST	27.00	67.2	75	No failure	Tensile	24.15	43	0.73 (4)	----	----
	CP-P9	ST	27.00	67.2	75	No failure	Micro	----	----	----	Yes	11 (c)
CPST Dome Rim	CP-R2	ST	0	0	0	No failure	Tensile	35.82	62	----	----	----
	CP-R3	ST	0	0	0	No failure	Tensile	33.01	57	----	----	----
	CP-R1	ST	0	0	0	No failure	Micro	----	----	----	No	12 (a)
	CP-R5	ST	18.00	48.2	50	No failure	Tensile	29.95	52	0.87	----	----
	CP-R6	ST	18.00	48.2	50	No failure	Tensile	33.64	59	0.98	----	----
	CP-R4	ST	18.00	48.2	50	No failure	Micro	----	----	----	No	12 (b)
	CP-R8	ST	27.00	72.3	75	No failure	Tensile	30.65	54	0.89	----	----
	CP-R9	ST	27.00	72.3	75	No failure	Tensile	25.21	44	0.73 (4)	----	----
	CP-R7	ST	27.00	72.3	75	No failure	Micro	----	----	----	Yes	12 (c)

(1) UTS_f = Residual strength of exposed specimen (failure load / original specimen cross sectional area)
(2) Percent tensile strength retained = UTS_f / UTS_i x 100 where UTS_i = average ultimate tensile strength obtained from baseline tensile tests of non-exposed specimens.
(3) Residual strength ratio = UTS_s/UTS_o where: UTS_s = residual strength of stressed and exposed specimen and UTS_o = averaged residual strength of non-stressed and exposed specimens.
(4) Passed if residual strength ratio ≥0.75, failed if ratio <0.75.

11.4 Appendix D: Summary of the Phase II SCC Test Results Following 30-day 3.5% NaCl Alternate Immersion Exposure

Table D-1. Phase II SCC test results for spin formed Al 2219-T62 aft bulkhead material following 30-day 3.5% NaCl alternate immersion exposure; LT orientation.

Coupon Blank	Specimen No.	Orientation	Applied Stress Level ksi	Applied Stress Level % Measured ST YS	Applied Stress Level % MMPDS LT YS	Days to Failure	Post SCC Test Evaluation	Residual Tensile Strength ksi[1]	Percent Tensile Strength Retained[2]	Residual Strength Ratio[3]	SCC? Metallo-graphic Examination	Photo-micrograph Figure No.
M7	M7-3	LT	0	0	0	No failure	Tensile	28.23	52	---	---	---
	M7-4	LT	0	0	0	No failure	Tensile	30.98	57	---	---	---
	M7-2	LT	0	0	0	No failure	Micro	---	---	---	No	A-1 (a)
	M7-6	LT	18.32	50	51	No failure	Tensile	22.75	42	0.77	---	---
	M7-7	LT	18.32	50	51	No failure	Tensile	29.65	55	1	---	---
	M7-5	LT	18.32	50	51	No failure	Micro	---	---	---	No	A-1 (b)
	M7-9	LT	27.48	75	76	No failure	Tensile	31.53	58	1.06	---	---
	M7-10	LT	27.48	75	76	No failure	Tensile	25.62	47	0.87	---	---
	M7-8	LT	27.48	75	76	No failure	Micro	---	---	---	No	A-1 (c)
	M7-13	LT	32.98	90	92	No failure	Tensile	28.51	53	0.96	---	---
	M7-14	LT	32.98	90	92	No failure	Tensile	25.04	46	0.85	---	---
	M7-12	LT	32.98	90	92	No failure	Micro	---	---	---	No	A-1 (d)
M8	M8-45	LT	0	0	0	No failure	Tensile	33.98	59	---	---	---
	M8-46	LT	0	0	0	No failure	Tensile	33.23	58	---	---	---
	M8-44	LT	0	0	0	No failure	Micro	---	---	---	No	A-2 (a)
	M8-48	LT	19.39	50	54	No failure	Tensile	32.54	56	0.97	---	---
	M8-49	LT	19.39	50	54	No failure	Tensile	32.68	57	0.97	---	---
	M8-47	LT	19.39	50	54	No failure	Micro	---	---	---	No	A-2 (b)
	M8-51	LT	29.09	75	81	No failure	Tensile	37.74	65	1.12	---	---
	M8-52	LT	29.09	75	81	No failure	Tensile	31.38	54	0.93	---	---
	M8-50	LT	29.09	75	81	No failure	Micro	---	---	---	No	A-2 (c)
	M8-55	LT	34.90	90	97	No failure	Tensile	32.84	57	0.98	---	---
	M8-56	LT	34.90	90	97	No failure	Tensile	37.41	65	1.11	---	---
	M8-54	LT	34.90	90	97	No failure	Micro	---	---	---	No	A-2 (d)
M9	M9-87	LT	0	0	0	No failure	Tensile	39.10	66	---	---	---
	M9-88	LT	0	0	0	No failure	Tensile	39.16	66	---	---	---
	M9-86	LT	0	0	0	No failure	Micro	---	---	---	No	A-3 (a)
	M9-90	LT	19.84	50	55	No failure	Tensile	38.96	65	1	---	---
	M9-91	LT	19.84	50	55	No failure	Tensile	40.5	68	1.04	---	---
	M9-89	LT	19.84	50	55	No failure	Micro	---	---	---	No	A-3 (b)
	M9-93	LT	29.76	75	83	No failure	Tensile	39.58	66	1.01	---	---
	M9-94	LT	29.76	75	83	No failure	Tensile	42.41	71	1.08	---	---
	M9-92	LT	29.76	75	83	No failure	Micro	---	---	---	No	A-3 (c)
	M9-97	LT	35.71	90	99	No failure	Tensile	34.08	57	0.87	---	---
	M9-98	LT	35.71	90	99	No failure	Tensile	39.06	66	1	---	---
	M9-96	LT	35.71	90	99	No failure	Micro	---	---	---	No	A-3 (d)
M10	M10-171	LT	0	0	0	No failure	Tensile	34.10	61	---	---	---
	M10-172	LT	0	0	0	No failure	Tensile	29.47	53	---	---	---
	M10-170	LT	0	0	0	No failure	Micro	---	---	---	No	A-4 (a)
	M10-174	LT	18.94	50	53	No failure	Tensile	31.51	56	0.99	---	---
	M10-175	LT	18.94	50	53	No failure	Tensile	29.44	53	0.93	---	---
	M10-173	LT	18.94	50	53	No failure	Micro	---	---	---	No	A-4 (b)
	M10-177	LT	28.40	75	79	No failure	Tensile	34.70	62	1.09	---	---
	M10-178	LT	28.40	75	79	No failure	Tensile	32.52	58	1.02	---	---
	M10-176	LT	28.40	75	79	No failure	Micro	---	---	---	No	A-4 (c)
	M10-181	LT	34.08	90	95	No failure	Tensile	30.03	54	0.94	---	---
	M10-182	LT	34.08	90	95	No failure	Tensile	34.24	61	1.08	---	---
	M10-180	LT	34.08	90	95	No failure	Micro	---	---	---	No	A-4 (d)

(1) UTS_f = Residual strength of exposed specimen (failure load / original specimen cross sectional area).

(2) Percent tensile strength retained = UTS_f / UTS_i x 100 where UTS_i = average ultimate tensile strength obtained from baseline tensile tests of non-exposed specimens.

(3) Residual strength ratio = UTS_s/UTS_o where: UTS_s = residual strength of stressed and exposed specimen and UTS_o = averaged residual strength of non-stressed and exposed specimens.

(4) Passed if residual strength ratio ≥0.75, failed if ratio <0.75.

Table D-2. Phase II SCC test results for spin formed Al 2219-T62 aft bulkhead material following 30-day 3.5% NaCl alternate immersion exposure; ST orientation.

Coupon Blank	Specimen No.	Orientation	Applied Stress Level ksi	Applied Stress Level % Measured ST YS	Applied Stress Level % MMPDS LT YS	Days to Failure	Post SCC Test Evaluation	Residual Tensile Strength ksi(1)	Percent Tensile Strength Retained(2)	Residual Strength Ratio(3)	SCC? Metallo-graphic Examination	Photo-micrograph Figure No.
M7	M7-24	ST	0	0	0	No failure	Tensile	28.40	49	----	---	---
	M7-25	ST	0	0	0	No failure	Tensile	18.61	32	----	---	---
	M7-23	ST	0	0	0	No failure	Micro	----	----	----	No	B-1 (a)
	M7-27	ST	21.60	50	60	No failure	Tensile	22.51	39	0.96	---	---
	M7-28	ST	21.60	50	60	No failure	Tensile	20.97	36	0.89	---	---
	M7-26	ST	21.60	50	60	No failure	Micro	---	---	---	No	B-1 (b)
	M7-29	ST	32.40	75	90	Failed; 30 days	Micro	----	----	----	Yes	B-1 (c1)
	M7-30	ST	32.40	75	90	Failed; 28 days	Micro	----	----	----	Yes	B-1 (c2)
	M7-31	ST	32.40	75	90	Failed; 26 days	Micro	----	----	----	Yes	B-1 (c3)
	M7-33	ST	38.88	90	108	Failed; 28 days	Micro	---	---	---	Yes	B-1 (d1)
	M7-34	ST	38.88	90	108	Failed; 26 days	Micro	---	---	---	Yes	B-1 (d2)
	M7-35	ST	38.88	90	108	Failed; 26 days	Micro	---	---	---	Yes	B-1 (d3)
M8	M8-66	ST	0	0	0	No failure	Tensile	23.25	40	----	---	---
	M8-67	ST	0	0	0	No failure	Tensile	19.44	33	----	---	---
	M8-65	ST	0	0	0	No failure	Micro	----	----	----	No	B-2 (a)
	M8-69	ST	21.87	50	61	No failure	Tensile	16.52	28	0.77	---	---
	M8-70	ST	21.87	50	61	No failure	Tensile	32.45	55	1.52	---	---
	M8-68	ST	21.87	50	61	No failure	Micro	---	---	---	No	B-2 (b)
	M8-72	ST	32.80	75	91	Failed; 30 days	Micro	---	---	---	---	---
	M8-71	ST	32.80	75	91	Failed; 30 days	Micro	---	---	---	No	B-2 (c1)
	M8-73	ST	32.80	75	91	Failed; 27 days	Micro	---	---	---	Yes	B-2 (c2)
	M8-77	ST	39.36	90	109	No failure	Tensile	22.51	38	1.05	---	---
	M8-75	ST	39.36	90	109	Failed; 26 days	Micro	---	---	---	Yes	B-2 (d1)
	M8-76	ST	39.36	90	109	Failed; 30 days	Micro	---	---	---	No	B-2 (d2)
M9	M9-108	ST	0	0	0	No failure	Tensile	26.95	45	----	---	---
	M9-109	ST	0	0	0	No failure	Tensile	19.55	33	----	---	---
	M9-107	ST	0	0	0	No failure	Micro	----	----	----	No	B-3 (a)
	M9-110	ST	22.17	50	62	No failure	Tensile	28.09	47	1.21	---	---
	M9-112	ST	22.17	50	62	No failure	Tensile	19.66	33	0.85	---	---
	M9-111	ST	22.17	50	62	Failed; 30 days(5)	Micro	---	---	---	---	---
	M9-114	ST	33.25	75	92	No failure	Tensile	24.50	41	1.05	---	---
	M9-115	ST	33.25	75	92	No failure	Tensile	27.58	46	1.19	---	---
	M9-113	ST	33.25	75	92	No failure	Micro	---	---	---	No	B-3 (b)
	M9-118	ST	39.90	90	111	No failure	Tensile	24.62	41	1.06	---	---
	M9-119	ST	39.90	90	111	No failure	Tensile	25.17	42	1.08	---	---
	M9-117	ST	39.90	90	111	Failed; 26 days	Micro	---	---	---	No	B-3 (c)
M10	M10-150	ST	0	0	0	No failure	Tensile	18.88	32	----	---	---
	M10-151	ST	0	0	0	No failure	Tensile	19.36	32	----	---	---
	M10-149	ST	0	0	0	No failure	Micro	----	----	----	No	B-4 (a)
	M10-152	ST	22.21	50	62	Failed; 29 days	Micro	---	---	---	Yes	B-4 (b1)
	M10-153	ST	22.21	50	62	No failure	Tensile	5.51	9	0.29(4)	Not Rated(6)	B-4 (b2)
	M10-154	ST	22.21	50	62	No failure	Tensile	2.56	4	0.13(4)	Not Rated(6)	B-4 (b3)
	M10-155	ST	33.31	75	93	No failure	Tensile	20.32	34	1.06	---	---
	M10-156	ST	33.31	75	93	Failed; 30 days	Micro	---	---	---	No	B-4 (c1)
	M10-157	ST	33.31	75	93	Failed; 26 days	Micro	---	---	---	Yes	B-4 (c2)
	M10-159	ST	39.37	90	109	Failed; 30 days	Micro	---	---	---	No	B-4 (d1)
	M10-160	ST	39.37	90	109	Failed; 29 days	Micro	---	---	---	No	B-4 (d2)
	M10-161	ST	39.37	90	109	Failed; 29 days	Micro	---	---	---	Yes	B-4 (d3)

(1) UTS_f = Residual strength of exposed specimen (failure load / original specimen cross-sectional area).

(2) Percent tensile strength retained = UTS_f / UTS_i x 100 where UTS_i = average ultimate tensile strength obtained from baseline tensile tests of non-exposed specimens.

(3) Residual strength ratio = UTS_s/UTS_o where: UTS_s = residual strength of stressed and exposed specimen and UTS_o = averaged residual strength of non-stressed and exposed specimens.

(4) Passed if residual strength ratio $\geq$0.75, failed if ratio <0.75.

(5) Invalid failure; failed in shoulder outside of gage length.

(6) Photomicrograph of exposed specimen taken after tensile testing.

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14. ABSTRACT
The principal focus of this project was to assist the Orion Multi-Purpose Crew Vehicle (MPCV) Program in developing a spin forming fabrication process for manufacture of the aft bulkhead of the pressure vessel. The spin forming process will enable a single piece aluminum (Al) 2219 aft bulkhead which will eliminate the current multiple piece welded construction, simplify fabrication, and lead to an enhanced design that will reduce vehicle weight by eliminating welds. This report is a supplement to the original publication (NASA/TM-2015-218674). Phase I (NESC-RP-12-00776/NASA TM-2014-218163, (1)) of this assessment explored spin forming the single-piece forward pressure vessel bulkhead from aluminum-lithium (Al-Li) 2195.

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